THE ROLE OF SELECTIVE ATTENTION FOR OBJECT INTEGRATION

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SUMMARY

Our brain has developed mechanisms, which structure and organize the complex visual input that we constantly perceive during everyday life. For instance, a given visual scene typically contains multiple sources of information that need to be structured and organized into meaningful perceptual units for higher-order capacity-limited processing. One mechanism that achieves an integration of the fragmented image parts into coherent whole objects is perceptual grouping. The organization of the visual environment by means of perceptual grouping appears to be achieved in a fairly effortless manner. However, whether such mechanisms of object integration operate automatically, or whether they depend on the engagement of attention is a matter of intense debate. The current dissertation aimed to investigate the role of attention in object completion in three different projects that combined methods from basic research with a clinical, neuropsychological, and neuroscientific perspective. The first project tested grouping of Kanizsa figures in both the impaired and the preserved hemifields of neuropsychological patients suffering from a hemifield-specific failure in selective attention. Results revealed that attention is only captured by salient groupings when it is not currently engaged elsewhere, thus showing that attention is indeed an integral part of object integration processes. The second project combined a behavioral task with eye gaze and pupil size measurements to elucidate the involvement of attention in perception and object integration. Results of two experiments indicated that perceptual grouping scales with the allocation of attention, provided that at least residual attentional resources are available to trigger the representation of a complete (target) object. Finally, by using transcranial magnetic stimulation (TMS), we investigated the causal contribution of the right parietal cortex for successful object integration in healthy participants. We found that this brain region seems to mediate the processing of object groupings. It up- and down regulates the deployment of attention to spatial regions where to-be-grouped items require attentional resources for object completion. Taken together, this dissertation provides new evidence that at least some residual amounts of attention are required to bind fragmentary parts into coherent whole percepts in the first place, such that these integrated objects can in turn capture attention.

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1. GENERAL INTRODUCTION

If you have ever tried to find Waldo in one of the many children's picture puzzle books by Martin Handford, then you have certainly experienced the topic of this dissertation in "real" life. These books consist of detailed, widespread illustrations of dozens of people and objects. The reader's task is to search for a character named Waldo who is hidden in this visually cluttered scene. Waldo can be identified by a red and white striped shirt, a bobble hat, glasses, and other targets such as a walking stick or a camera. But how can we successfully find Waldo and what kind of processes help us identifying him among this huge amount of visual information? Let us try to find out together over the course of this dissertation.

This introduction, and therefore the first part of my dissertation, is intended to give an overview of the most important principles and findings underlying the current topic of this work on "The role of selective attention for object integration". In the following, I will shortly explain the term selective visual attention, continue by giving insights into the mechanism of object integration and finally, I will highlight the relationship between these two principles and present the aims of this thesis.

1.1. SELECTIVE VISUAL ATTENTION

Each time we open our eyes, we are confronted with a vast amount of visual information that is out there in the world. Surprisingly, however, we are not overwhelmed by our visual world but instead seem to understand and interact with it effortlessly. How is this possible? The simple answer is that our visual experience is guided by "attention". It helps us to separate the relevant information from irrelevant noise and allows us to selectively process information and prioritize some aspects of information over others by focusing on certain facets of the visual scene (Carrasco, 2011). Such mechanisms of selective attention are essential because of the limited capacity of our brain to process information (Lennie, 2003; Carrasco, 2011).

The most prominent approaches explaining how attention is modulated are the gradient theory (Downing & Pinker, 1985; LaBerge & Brown, 1989), the zoom-lens model (Eriksen & Yeh, 1985), the single spotlight theory (Posner, 1980) and the multiple spotlights theory of attention (Awh & Pashler, 2000). All these theories assume that attention selects a specific spatial area of our surroundings, which in turn gets processed more efficiently. According to the gradient theory, attentional resources are highest at the center of the focus, the so-called fovea. The fovea is a small central region of the retina which comprises a high concentration of cone photoreceptors and therefore allows for high visual acuity (Pouget, 2019). The larger the visual angle of a stimulus from the fovea, the lower the expected amount of available attentional resources (Jacobs, 1979; Downing & Pinker, 1985; LaBerge & Brown, 1989; Ducrot & Grainger, 2007). A comparable logic applies to the zoom-lens model according to which the focus of visual attention can change in size (narrow focus or widely distributed across a large part of the visual field) (Eriksen & Yeh, 1985; Schad & Engbert, 2012). The spotlight theory on the other hand states that attention is more like a spotlight which focuses on subsequent stimuli in a serial manner (Posner, 1980; VanRullen, Carlson, & Cavanagh, 2007). Finally, the multiple spotlight theory assumes that we can split and allocate our attention to different non-adjacent regions of visual space (Awh & Pashler, 2000; Eysenck & Keane, 2010).

Despite all differences, these accounts commonly assume that the size of the attended region can be adjusted voluntarily thereby enhancing the processing of visual stimuli in the respective area (Carrasco, 2011). Interestingly, however, the distribution of attention over a large area of the visual field (in comparison to being focused on just one precise position) corresponds to a loss of spatial resolution and processing efficiency (see for example Eriksen & Murphy, 1987; Eriksen, 1990; Castiello & Umilta, 1990, 1992).

If spatial attention is oriented to a specific location by moving the eyes one speaks of "overt attention", while "covert attention" describes the orienting process without directing the gaze towards the specific location. Moreover, covert attention can be deployed to more than just one location simultaneously while eye movements are naturally sequential (Carrasco, 2011). While overt attention is known to be easily recordable by tracking the eye gaze for a long time, covert attention was only recently successfully linked to the recording of the pupil size (for a review see Mathôt, 2020).

Together, selective attention improves our perception and performance by modifying our sensory input, thereby enhancing representations of the relevant while ignoring less relevant locations or features of our surroundings (Mangun, 1995; Carrasco, 2011). Whether selective attention is a process necessary for successful object integration is the topic of the present dissertation.

1.2. OBJECT COMPLETION

Perceiving objects seems to be a fast, automatic and effortless process in our daily live. This process, however, is rather complex: boundaries of objects need to be detected in order to identify available perceptual units. These units have to be segmented from other objects and the background (Cornsweet, 1970; Marr, 1982; Chen, Glasauer, Müller, & Conci, 2018). Moreover, even in situations with degraded ambient luminance conditions, separate visual parts need to be structured, organized and finally integrated into a unified whole (Chen et al., 2018; Scherzer & Faul, 2019).

In human visual perception, there are mechanisms which give rise to the perception of a whole object despite parts of the object not actually having a correspondence (Scherzer & Faul, 2019). Those processes are known as "perceptual completion". Commonly, two different types of completion are differentiated, namely modal and amodal completion (Michotte & Burke, 1951; Burke, 1952; Glynn, 1954; Michotte, Thinès, & Crabbé, 1964/1991). On one hand, modal completion describes a filling-in process such as the connection of fragmented image parts into a complete visible perceptual figure (Michotte et al., 1964/1991; Scherzer & Faul, 2019). Importantly, this term refers to the perception of unoccluded parts of objects which are not delimited by physical differences (e.g., luminance, texture) and appear with sensory characteristics such as an observable brightness enhancement of the completed region. Amodal completion, on the other hand, is characterized by the perception of the occluded parts of objects and the absence of sensory aspects and will not be further discussed in the course of this dissertation (Kellman & Shipley, 1991; Scherzer & Faul, 2019).

Object completion is usually supported by a set of organizational principles which were first described by Gestalt psychologists (Wertheimer, 1923; Koffka, 1935). They demonstrated that the organization of visual information relies on basic principles such as similarity, closure, collinearity, good continuation, and proximity, which are assumed to be the mechanisms generating perceptual units as a basis for subsequent analyses (Wertheimer, 1923; Koffka, 1935; Gillam, 1987). These principles are all summarized under the term "Prägnanz" which states that humans structure visual input in such a way that the resulting perceptual experience is regular, orderly and simple (Wertheimer, 1923; Koffka, 1935). The principle *similarity* for example assumes that objects which are similar are grouped together. Elements which are symmetric with respect to a straight line, on the other hand, will be grouped together (*collinearity*), while elements which are close to each other also tend to form a group (*proximity*). The principle of *closure*, finally, describes the process that elements which form a closed shape are perceived as belonging together (Wertheimer, 1923; Koffka, 1935; Todorovic, 2008).

One famous example of modal completion on the basis of collinearity and closure is the Kanizsa figure (Figure 1; Kanizsa, 1955, 1976; Conci, Müller, & Elliott, 2007). This figure consists of black circles with cut-out segments. The missing parts induce the illusion of a bright shape, which seems to overlie the black circles. Such an illusory figure thus lacks a corresponding physical object. In line with the above-described concepts, the Kanizsa figure is characterized by a brightness enhancement of the illusory area, where the central shape (i.e., diamond) reveals precise boundaries (illusory contours) without a corresponding physical correlate and this shape is organized in depth (i.e., it is perceived as lying above the circular inducer elements; Kanizsa, 1976; Kogo, Strecha, Van Gool, & Wagemans, 2010; Scherzer & Faul, 2019). The Kanizsa figure thus illustrates the process of object completion from fragmented image parts into a coherent unit.

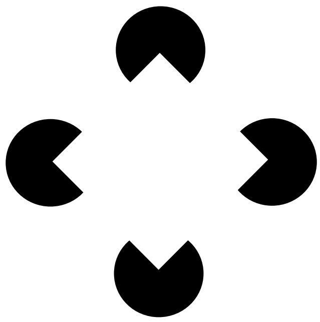

Figure 1. Example of a Kanizsa figure adapted from Kanizsa (1976). Based on collinearity and closure, we perceive an illusory white diamond, which seems to have distinct contours, appears brighter than the background (despite the color of the inner and outer region being identical) and gives the impression of being superimposed on black dots. When taking a closer look, the contours of the diamond disappear since they are subjective and thus lack a corresponding physical object.

1.3. SELECTIVE ATTENTION AND VISUAL OBJECT INTEGRATION

What role does selective attention play in object integration? There has been an extensive debate in the literature over the last 30 years on whether attention is necessary for perceptual grouping. Influential theories such as the feature integration theory (FIT) (Treisman & Gelade, 1980) assume that attention must first be allocated to a given stimulus in order to enable the integration of featural parts into complete-object representations. In this view, object completion would only generate a coherent whole when we attend a given location. More precisely, at the core of their theory was the idea of distinct feature maps such as colors, basic shapes, or other properties. Thus, the visual scene is initially encoded along these dimensions. While a singleton in a feature map (for example a green bar against a field of red bars) would be detected effortlessly without the need of attention because of the unique occurrence of a feature in a retinotopic map, conjunctions of features cannot be handled by such a parallel operation of single feature maps by themselves. Instead, attention is needed to bind features at a more central position, namely a master map of locations, in order to perceive a whole object (Treisman & Gelade, 1980; Nakayama & Martini, 2011).

Other theories, however, suggest that the representation of complete objects arises “preattentively”, that is, prior to the engagement of attention (Humphreys, Romani, Olson, Riddoch, & Duncan, 1994; Mattingley, Davis, & Driver, 1997; Driver & Baylis, 1998; Scholl, 2001). Thus, opposing viewpoints postulate that object integration arises either before or after attention is allocated to a given stimulus.

A key approach for investigating whether selective attention is required for visual object integration is the visual search paradigm in which observers are asked to search for an odd or predefined target (Treisman, 1982). Treisman’s Feature Integration theory had the greatest impact on the importance of this paradigm since the visual search paradigm provided the basis of the data for her theory (Nakayama & Martini, 2011). Searching for single features in a visual scene is considered efficient since reaction time is independent of display size and the number of non-target elements. The single features, thus, seem to pop out and the underlying processes are assumed to operate quickly, automatically and in parallel. Conjunction search, on the other hand, is relatively inefficient since reaction time increases with each additional element, creating a relatively steep search slope for target present vs. absent responses. This prolongation of response time as a function of the number of distractors denotes a serial search of target features. Hence, visual search can occur in two modes: pre-attentive (feature search) and attentive (conjunction search) (Nakayama & Martini, 2011).

In response to findings of the FIT theory, several other studies showed that salient targets (e.g. Kanizsa figures) automatically attract attention, and thus pop out, during a visual search task (Gurnsey, Humphrey & Kapitan, 1992; Davis & Driver, 1994; Rauschenberger & Yantis, 2001; Senkowski, Rottger, Grimm, Foxe, & Herrmann, 2005; Wiegand, Finke, Töllner, Starman, Müller, & Conci, 2015; Kimchi, Yeshurun, Spehar, & Pirkner, 2016; see also Conci et al., 2007; Conci, Böbel, Matthias, Keller, Müller, & Finke, 2009). Davis and Driver (1994), for example, presented Kanizsa figures among a varying number of non-targets (i.e., distractors) and found that reaction times were faster for detecting target-present as compared to target-absent trials while being independent from the number of non-tragets. In the study of Senkowski and colleagues (2005) participants also had to detect the presence of a Kanizsa target within a non-symmetric arrangement of inducer disks. Again, reaction times were faster for target-present trials and only a small increase of reaction times was observable when increasing the set size (i.e., number of distractors). These results were taken to indicate that Kanizsa figures pop out, i.e., search for an integrated target object is based solely on preattentive processing. That is, the perception of Kanizsa figures does not require focal attention in the first place but rather captures spatial attention and attracts attentional resources (as opposed to the FIT).

The assessment of brain damaged patients with impairments of attentional functioning is another promising approach to this longstanding controversy (Driver, 1995; Kerkhoff, 2001). The clinically most telling impairments of selective attention are demonstrated by patients suffering from visual hemi-neglect or associated extinction behavior caused by very large right-sided lesions with a center on the right inferior parietal cortex while also extending into the temporal, occipital and frontal cortex as well as subcortical structures (Vallar & Perani, 1986; Kerkhoff, 2001; Karnath, Milner, & Vallar, 2002; Fink & Heide, 2004). Patients with such brain lesions are diagnosed with either unilateral visuo-spatial (hemi-)neglect, which is characterized by the impaired ability to process or respond to visual stimuli in the contralateral hemispace (Kerkhoff, 2001; Karnath et al., 2002; Fink & Heide, 2004), or with associated extinction behavior, which is defined as a deficit of detecting a contralesional stimulus when presented together with a second, ipsilesional stimulus (Umarova, Saur, Kaller, Vry, Glauche, Mader, & Weiller, 2011). By definition, however, the basic visual processing of single, unilateral stimuli has to be intact in patients with extinction behavior (Kerkhoff, 2001). Moreover, the impaired or lost ability to process information in one half of the visual field cannot be explained by primary sensory deficits only, but is due to an unilateral impairment in selective visual attention (Posner & Driver, 1992; Kerkhoff, 2001). Classical diagnostic tools involve, for example, the line bisection tasks in which patients usually place their bisection mark too far to their ipsilesional side, or the copy task in which patients fail to reproduce the left part of an object (Wilson, Cockburn, & Halligan, 1987; Kerkhoff, 2001; see Figure 2 for examples).

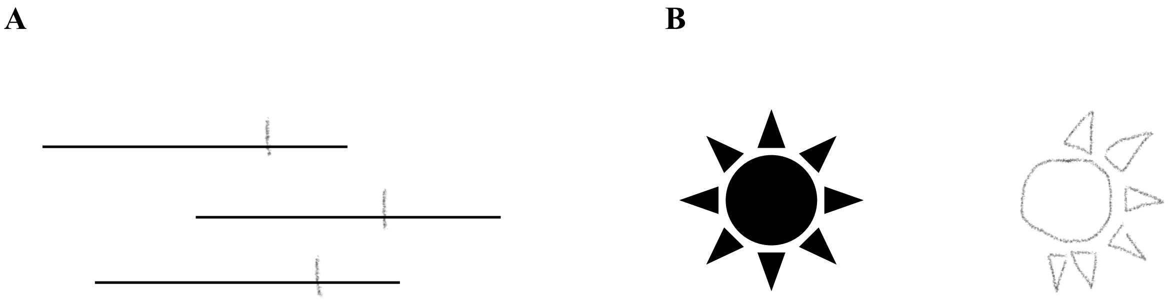

Figure 2. Exemplary performance of a potential patient suffering from visual hemi-neglect (A) in a line bisection task and (B) in a copy task adapted from the Behavioral Inattention Test (BIT; Wilson et al., 1987).

The majority of recent findings from neglect and extinction studies supports the view that object integration is achieved prior to the engagement of attention (Driver & Baylis, 1998; Humphreys, 2016; for a review see Scholl, 2001), thus also opposing the view as predicted by feature integration theory (Treisman & Gelade, 1980). Such "preattentive" processes are known to occur early, to be fast and automatic and to include the perception of features that seem to "pop-out" during visual processing (Treisman, 1982; Humphreys, Romani, Olson, Riddoch, & Duncan, 1994; Mattingley et al., 1997; Driver & Baylis, 1998; Scholl, 2001). A prominent example of such an "object-based" view of attention was provided in a study by Mattingley et al. (1997). They tested a patient in a visual search task who showed left-sided extinction behavior due to right-hemisphere brain damage. The patient had to detect the removal from four circles (two in each hemifield) while the segments could be removed from both sides (bilaterally), from only one side (unilaterally) or not at all (catch trials). In "inner" displays, the arrangement of bilaterally removed segments induced the emergence of a Kanizsa figure (i.e., a white rectangle). No such illusory percepts occurred in "outer" displays due to outward facing segments. The authors showed that the typical extinction behavior completely vanished whenever bilateral segments could be grouped together in order to form a complete Kanizsa figure by linking the stimuli across both hemifields (see also Conci et al., 2009). Substantial extinction, however, was still present for bilateral "outer" displays. The fact that the extinction patient could integrate the features into a whole percept despite severe attentional deficits was taken as evidence that object integration occurs without the engagement of attention.

Opposite to the above-mentioned findings, several traditional attention models report that attention is indeed necessary for successful binding of visual parts into a coherent whole object (Treisman & Gelade, 1980; Kahneman, Treisman, & Gibbs, 1992; Wolfe & Cave, 1999). More recent studies support this view. Gögler, Finke, Keller, Müller, and Conci (2016), for example, combined two of the above-mentioned approaches: they presented extinction patients a visual search task and asked them to spot the presence (vs. absence) of a Kanizsa figure presented alone or together with a distractor. Results of target-present trials showed that patients were slower in detecting the Kanizsa target when the distractor created a disturbing perceptual shape in the attended, right hemifield. This was not the case, however, when the distraction emerged in the unattended, left hemifield which was taken to suggest, that there is only an advantage for attended object parts.

Furthermore, a follow-up study replicated the basic Kanizsa figure experiment presented by Mattingley et al. (1997): Conci, Gross, Keller, Müller, & Finke (2018) additionally tested the effect of grouping direction, i.e., whether object integration is predominantly executed from within the impaired or from the attended visual field. The results in this study showed that a clear reduction of extinction by means of grouping was only evident when grouping departed from the attended side, but not when grouping departed from the extinguished hemifield. Thus, these results might in fact suggest that attention behaves like the "glue" for object integration in parietal extinction with grouping essentially extending with the spreading of attention to fragments in the neglected hemifield (Conci et al., 2018).

To date, there are several controversial findings concerning the role of selective attention for object integration. While older studies often support the object-based view, more recent results with neuropsychological patients suggest a crucial role of attention in integration processes.

1.4. AIMS OF THIS THESIS

The aim of this dissertation was to further investigate the role of selective visual attention for object integration, since this is still a controversial topic. Thus, further studies are necessary to support recent preliminary results suggesting attention to be an integral part of perceptual grouping processes (i.e., Gögler et al., 2016; Conci et al., 2018) and to extend these findings to healthy subjects.

For this purpose, classical psychophysical methods as well as other objective neuroscientific measures such as eye-tracking and transcranial magnetic stimulation (TMS) were used. Furthermore, a study with neuropsychological patients who showed a deficit in visual attention as a result of parietal brain damage was performed. In all studies, participants were asked to detect targets which were either embedded in different configurations of Kanizsa figures or which were not integrable into a coherent global percept. More precisely, this thesis consists of the following projects and concomitant, explicit aims.

1.4.1. PROJECT 1

This first study investigated the role of visual attention by testing grouping in Kanizsa figures in solely the neglected or the attended hemifield of patients suffering from extinction as a result of parietal brain damage (Mattingley et al., 1997; Conci et al., 2009; Conci et al., 2018). More precisely, we wanted to compare hemifield-specific grouping processes, that is, configurations which do not allow attentional spreading across hemifields along the grouped object, in order to assess whether a substantial reduction of extinction requires available attentional resources (as reported in Conci et al., 2018). In bilateral shape conditions (i.e., simultaneous presentation of two targets, one in each hemifield), the patients had to detect lateral "pacman" targets that can be integrated into a whole illusory diamond-like object, whereas in the unilateral shape conditions (i.e., only one target) an illusory triangle was presented either on the left or on the right side of the visual field. Critically, however, grouping of the triangles always proceeded from the central midline, thus allowing testing the efficiency of hemifield-specific grouping. The patients' task was to indicate which quarter-segments were removed in each trial: either from left circles, right circles, both sides, or neither side (Conci et al., 2009; Conci et al., 2018).

1.4.2. PROJECT 2

The process of allocating one's attention toward a target outside the center of eye fixation is known as covert attention (Posner, 1980; Carrasco, 2011). Several studies show that directing attention to a specific location results in greater resource allocation to the attended location, which in turn reduces the available resources at the unattended location (Tootell, Hadjikhani, Mendola, Marrett, & Dale, 1998; Somers, Dale, Seiffert, & Tootell, 1999; Slotnick, Schwarzbach, & Yantis, 2003; Beck & Kastner, 2009). Moreover, recent studies established that pupil size is specifically linked to attentional shifting (Daniels, Nichols, Seifert, & Hock, 2012; Brocher, Harbecke, Graf, Memmert, & Huttermann, 2018; Ivanov, Lazovic, and Mathôt 2019; Mathôt & Ivanov, 2019; Klatt, Noël, & Brocher, 2021; see also Mathôt, 2020). In Project 2, we thus measured eye gaze and pupil size in healthy participants while they performed a Kanizsa figure discrimination task. In two experiments, variants of Kanizsa figures (that either lead to the perception of an illusory figure, or where the configuration could not be integrated into such a coherent whole) were presented outside of the center of fixation (at varying eccentricities; first experiment), or while engaging attentional resources in an additional task at central fixation (second experiment). With these two experiments, we wanted to measure attention based on pupil size variations in order to systematically assess its influence on grouping processes.

1.4.3. PROJECT 3

Finally, in Project 3 we used transcranial magnetic stimulation (TMS) to test the causal contribution of the right parietal cortex for successful object integration in healthy participants. TMS is a non-invasive brain stimulation method, wherein a coil generating a magnetic field is held over the scalp. The rapidly changing electrical current stimulates the brain area directly under the coil, causing the neurons to be activated. If these neurons are involved in a cognitive function, such as selective attention towards a given stimulus configuration, then stimulating these neurons should briefly disrupt this specific function (Ward, 2015). For example, neglect-like behavior has repeatedly been induced by TMS stimulation over the right parietal cortex in healthy participants (see Sack, 2010 for a review). TMS could potentially provide valuable insights into the causal relationship between the role of the parietal cortex and its resulting attentional deficits while testing the performance of an object integration task adapted from Project 1 in healthy volunteers. The posterior part of the intraparietal sulcus was chosen as stimulation site since it is thought to be particularly important for the allocation of visual spatial attention to the contralateral hemifield (Gillebert, Mantini, Thijs, Sunaert, Dupont, & Vandenberghe, 2011). We expected intraparietal sulcus TMS to specifically influence the selection and processing of (grouped) objects.

In summary, all three projects aimed to show that attentional processes are the “glue” necessary for successful object integration, thereby supporting recent findings. The next chapter will present each of the studies and results in a detailed manner.

2. CUMULATIVE THESIS

This dissertation consists of three different studies: one peer-reviewed article that was published in the journal "Cortex" in 2021 (2.1.), one manuscript which was submitted for publication and is currently under review in the peer-reviewed journal "Attention, Perception & Psychophysics" (2.2.) and an additional, third manuscript, which is to be submitted in the near future (2.3.).

2.1. ATTENTION CAPTURE BY SALIENT OBJECT GROUPINGS IN THE NEGLECTED VISUAL FIELD

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The author of this dissertation collected and analyzed the data, created plots and interpreted the results, and wrote the manuscript. Kathrin Finke designed the experiment and helped revise the manuscript. Anna Lena Biel helped with collecting data and commented on the manuscript. Ingo Keller recruited the participants, examined medical records and confirmed the diagnostic status of participants. He also created the lesion mapping figure. Hermann J. Müller commented on and helped revise the manuscript. Markus Conci designed, programmed and supervised the experiment. He also contributed to the interpretation of the results and critically revised the manuscript.

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Research Report

Attention capture by salient object groupings in the neglected visual field

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ABSTRACT

The integration of fragmentary parts into coherent whole objects has been proposed either to rely on the availability of attentional resources or to arise automatically, that is, from preattentive processing (prior to the engagement of selective attention). In the present study, these two alternative accounts were tested in a group of neglect patients with right-hemisphere parietal brain damage and associated deficits of selective attention in the left (visual) hemispace. The reported experiment employed a search task that required detection of targets in the left and/or right hemifields, which were embedded in configurations that consisted of variants of Kanizsa figures. The results showed that a salient, grouped Kanizsa triangle presented within the unattended, left hemifield can substantially improve contralesional target detection, though the very same triangle configuration does not facilitate target detection in the impaired hemifield when presented together with an ipsilesional, but non-salient (i.e., structurally non-integrated, isolated) target. That is, attention is captured by the grouped object in the impaired hemispace only when it is not engaged in the processing of an (isolated) object in the attended hemispace. This demonstrates that both part-to-whole-object integration and search guidance by salient, integrated objects crucially require attentional resources.

1. Introduction

Natural environments usually contain multiple sources of information, several of which may be simultaneously task-relevant. However, given the limited capacity of the visual system, it is essential to structure and organize the complex visual input into meaningful perceptual units for efficient processing and adequate interaction with the environment. One mechanism involved in this is perceptual grouping,

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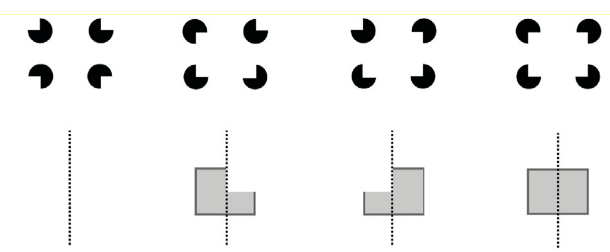
supporting the integration of fragmented image parts into complete objects. Koffka (1935) and Wertheimer (1923) were the first to describe grouping processes in terms of organizational principles, or 'laws', that govern the formation of higher-order units. In this view, object integration organizes non-contiguous parts into coherent whole objects, or 'Gestalten', by linking edges and segments according to principles of collinearity and closure (for a review see Wagemans et al., 2012). One prominent example is the "Kanizsa figure" (Kanizsa, 1976), where the arrangement of several disks with missing quarter-segments creates a vivid impression of an illusory object, such as the shape of a square, that lacks a corresponding physical object (see Fig. 1, right). Kanizsa figures thus illustrate how wholes are generated from fragmentary visual information.

The organization of the natural environment by means of perceptual grouping appears to operate in a fairly effortless manner and provides rather unambiguous interpretations of objects in our ambient array. Yet, it has been debated whether such grouping operations reflect a low-level automatic, "pre-attentive" process or whether object integration arises from higher-level cognitive functions that depend on the engagement of attention. That is, opposing viewpoints postulate that object integration arises either before or after attention is allocated to a given, to-be-integrated object. In fact, whether or not attention is critical for the perception of complete objects has led to the formulation of influential, opposing theories of visual perception (Driver & Baylis, 1998; Treisman & Gelade, 1980), and this question has since remained a controversial issue. To contribute to a resolution, in the current study, we tested the role of attention for the integration of parts into wholes by assessing object completion mechanisms in neglect patients, who typically exhibit deficits of selective attention in the left hemispace following right-hemispheric brain damage. Our experiment presented a visual search task requiring detection of target items in the left and the right visual field, which were embedded in configurations that systematically varied perceptual grouping in the two hemifields (e.g., a Kanizsa triangle in the left, or right half of the display). This setup was designed to determine whether perceptual grouping in the attended vs. unattended hemispace of the neglect patients would be equally efficient in modulating target detection performance.

As in the current study, in many previous studies, a key approach for investigating whether selective attention is required for visual object integration has been to assess brain-damaged patients with impaired attentional functioning. For instance, impairments of selective attention have been demonstrated in patients suffering from visual hemi-neglect and associated extinction behavior (Driver, 1995; Kerkhoff, 2001). Contralesional visuo-spatial neglect is characterized by the failure to attend, respond adequately, or orient voluntarily to stimuli in the contralesional hemispace (Karnath, Milner, & Vallar, 2002; Kerkhoff, 2001). These behavioral deficits typically occur in the left hemispace—as a result of right-hemispheric brain lesions, predominantly in the right inferior parietal cortex (in particular, in the angular and supramarginal gyrus) and in the right temporoparietal junction (Karnath et al., 2002; Kerkhoff, 2001). Importantly, in these patients, failure to process visual information in the left hemispace cannot be explained by primary sensory or motor deficits; rather, the observed deficits in performance result



	Ungrouped	Rightward	Leftward	Kanizsa
Mattingley et al. (1997)	17%			78%
Conci et al. (2009)	23%		79%	82%
Conci et al. (2018)	35%	48%		72%
	✗	✗	✓	✓

Fig. 1 – Examples of stimuli as used in previous studies (Conci et al., 2009, 2018; Mattingley et al., 1997), depicting bilateral configurations of ungrouped (left), partially grouped (middle), and complete Kanizsa figures (right). Partial groupings could either extend into the right or the left hemifield. For each configuration, the arrangement of inducers is depicted in the top row, along with an (idealized) illustration of the resulting integrated object in the bottom row. In addition, for each of these configurations, the associated mean percentages of correct detections of left-sided (Mattingley et al., 1997) and, respectively, bilateral (Conci et al., 2009, 2018) targets are provided. Red cross and green check marks illustrate whether the respective configurations were associated with substantial extinction behavior or, respectively, a reliable reduction of extinction behavior.

from a unilateral impairment in selective visual attention (Kerkhoff, 2001; Posner & Driver, 1992). A phenomenon that is associated with visual neglect is extinction behavior, which is also often classified as a mild form of neglect (Umarova et al., 2011). Extinction manifests in a failure to detect a contralesional stimulus when this is presented together with a second, ipsilesional stimulus, despite intact processing of single, unilateral stimuli in either hemispace (Kerkhoff, 2001). Thus, both visual extinction and neglect appear to arise from a competitive disadvantage of selection from the contralesional hemispace due to disrupted processes of selective attention (Baylis, Driver, & Rafal, 1993; Humphreys, Romani, Olson, Riddoch, & Duncan, 1994). The deficit, however, is relative rather than absolute, indicative of fewer attentional resources being allocated to the contralesional than to the ipsilesional side (Bays, Singh-Curry, Gorgoraptis, Driver, & Husain, 2010; Conci, Gross, Keller, Müller, & Finke, 2018; Gögler, Finke, Keller, Müller, & Conci, 2016).

Early findings from neglect and extinction studies support the view that object integration is achieved prior to the engagement of attention (Driver & Baylis, 1998; for a review see Humphreys, 2016; Scholl, 2001), thus arguing against the notion that attention must first be allocated to a given stimulus to enable the integration of fragmented image parts into a coherent whole object (e.g., as suggested by feature integration theory; Treisman & Gelade, 1980). A prominent example supporting such an "object-based" view of attention was provided by Mattingley, Davis, and Driver (1997). In their study, a patient with parietal brain lesions and associated extinction behavior was presented, in a series of experiments, with variants of Kanizsa figures that give rise to the perception of a grouped, illusory object. The typical experiment presented a sequence of displays with four disks arranged to form a square around central fixation. On each trial, quarter-segments were briefly removed from the disks either from the left, from the right, from both sides, or not at all. The task was to detect the side of the offsets. Removal of these segments on either the left or the right side of the display (i.e., presentation of unilateral left or right targets) did not impair performance.[1] However, there was severe extinction when the segments were removed from both sides (bilateral targets) under conditions in which these bilateral segments were oriented such that no grouping emerged (see Fig. 1, Ungrouped): the patient failed to detect more offsets on the left side when these were presented together with offsets on the right side (compared to unilateral left presentations). Crucially, extinction was much less severe when the disks in two hemifields formed a coherent Kanizsa square across the two sides (see Fig. 1, Kanizsa). That is, the typical extinction behavior vanished when bilateral segments could be grouped into a complete object across both hemispaces (see also Conci et al., 2009). The finding that the formation of integrated objects was preserved in the extinction patients despite severe attentional deficits was taken as evidence that object completion occurs without the engagement of attention (see also Vuilleumier, Valenza, & Landis, 2001).

Further support for object integration occurring at preattentive processing stages comes from studies with healthy observers, which concluded that an integrated object (e.g., a Kanizsa figure) may act as a salient cue that automatically attracts attention independently from the observer's goals (e.g., Kimchi, Yeshurun, Spehar, & Pirkner, 2016; Rauschenberger & Yantis, 2001; Senkowski, Rottger, Grimm, Foxe, & Herrmann, 2005; Wiegand et al., 2015). For example, Kimchi et al. (2016) asked their participants to detect the presence of a target (a Vernier stimulus) within an array of circular elements. On some of the trials, a subset of these elements was organized such that they formed a coherent whole object (a Kanizsa figure), and the target could appear either inside or outside of this grouped object. Faster responses were observed when the target appeared within the illusory figure, as compared to when no grouped object was presented. Moreover, responses were slowest when the target was presented outside the grouped object. This modulation of target detection latencies was obtained even though the grouped object was completely task-irrelevant and not predictive of the target location—which was taken to indicate that illusory figures can capture attention automatically. Moreover, the critical reaction time effect was found to scale with the strength of perceptual organization, indicating that more salient illusory figures are more potent attractors of attention (see also Conci, Müller, & von Mühlenen, 2013).

Besides attentional capture effects in healthy observers, the assessment of patients with visual hemi-neglect provides a valuable approach for investigating whether complete objects are integrated automatically, that is, without the engagement of focal attention. If grouping is accomplished without the engagement of attention, then neglect patients should show effects of such preattentive grouping. Accordingly, one would expect salient, attention-attracting groupings in the left, neglected hemispace to influence visual search performance comparably to groupings in the right hemispace. However, recent studies with visual neglect patients yielded no consistent evidence of such a grouping-dependent modulation of attentional priorities in the left hemispace. For instance, Gögler et al. (2016) had extinction patients perform a visual search task that required them to discern the presence (vs. absence) of a Kanizsa-figure target presented alone or together with a task-irrelevant nontarget. For the critical target-present trials, the results showed RT costs in detecting the fully grouped illusory object when the nontarget induced a distracting shape grouping, but only if the latter emerged in the attended (right) hemifield. Conversely, there was no comparable cost when the distracting shape grouping was presented in the unattended (left) hemifield. This pattern suggests a competitive advantage only for right-grouped—that is: attended—object parts. Moreover, in addition to replicating Mattingley et al.'s (1997) critical finding—of a reduction of extinction when bilateral targets could be integrated to form a Kanizsa square —, Conci et al. (2009, 2018) varied the grouping

[1] Unilateral left displays typically do not lead to extinction behavior even though the circles with removed quarter-segments on the left, unattended side (the targets) are presented together with two full circle placeholders on the right, attended side (Mattingley et al., 1997; Conci et al., 2009, 2018). Of note, though, the placeholder circles are not directly task-relevant (i.e., the target is a gap in the circle, rather than the circle itself) and thus do not compete strongly for attentional resources. Given this, the full circles per se do usually not induce extinction in this paradigm.

strength of the presented Kanizsa configurations. When the patients were presented with "partial" groupings such that object completion emerged primarily from the attended hemifield (see Fig. 1, Leftward), the degree of extinction was substantially reduced, to a level comparable to that with "fully" grouped Kanizsa figures (Fig. 1, Kanizsa; Conci et al., 2009). In contrast, when (in a follow-up study: Conci et al., 2018) patients were again presented with partial groupings, but with the completed object emerging primarily from the unattended hemifield (in the critical condition), the grouping was not successful to remedy visual extinction behavior (see Fig. 1, Rightward). Together, these studies show that the grouping direction—that is, whether object integration proceeds from the intact, attended hemispace, or from the unattended, impaired hemispace—determines whether or not a reduction of extinction becomes manifest. Conci et al. (2018) took this to suggest that attention may provide some "glue" that binds separate parts into coherent objects: In extinction and neglect patients, this "glue" seems to be lacking in the unattended hemispace, leading to impaired object integration processes, as a result of which Kanizsa figures are processed comparable to non-integrated, non-salient object configurations.

While these results appear to indicate—in contrast to many previous studies—that attention is crucial for object integration, the reported findings can only be considered preliminary evidence. Of note, almost all previous studies investigating grouping in extinction patients presented configurations that extended across both hemifields (see examples above). Conci et al. (2009, 2018) presented "partial" groupings where completion processes would originate from either the attended or the unattended hemifield. Nevertheless, these configurations did also extend across both hemifields (see Fig. 1) and so might have instigated some cross-hemispheric linkage in the first place that, in turn, fosters the subsequent spreading of attention from one hemifield to the other. It thus remains unclear whether hemifield-specific object groupings—that is, configurations that do not afford attentional spreading across hemifields along the grouped object—would yield a comparable result pattern to that found in the combined Conci et al., 2009 and 2018 studies, namely, that a substantial reduction of extinction depends on the availability of attention. The primary aim of the present study was to address this issue, by introducing and comparing object groupings that were restricted to the attended versus the unattended hemispace of neglect patients. Moreover, in comparing hemifield-specific grouping processes within the attended versus the unattended hemifield, a secondary aim was to examine for potential variations in performance in a within-subjects design (instead of the comparison between separate groups that participated in the two Conci et al., 2009 and 2018, studies), so as to ensure that any differential effects between the two conditions cannot not be attributed to accidental differences in the samples of patients tested.

To this end, new variants of Kanizsa figures were designed and presented in the impaired and the attended hemifields, in a single group of patients suffering from visual extinction. Critically, rather than implementing square configurations as in previous studies (Conci et al., 2009, 2018; Mattingley et al., 1997), the new variants were composed of four disk elements arranged in diamond form—with the patients being required to indicate whether segments were removed from the left disk, the right disk, from both disks, or not at all, while ignoring the (distractor) disks at the top and bottom of a given configuration (see Fig. 2A). Compared to the (square) stimuli employed in previous studies, this new design provided more experimental control over the exact region of space where an illusory figure would emerge, essentially permitting grouping to be varied independently within each half of the display.

To elaborate, groupings consisted of either an illusory Kanizsa figure ('diamond') that spread across both hemifields, or an illusory figure ('triangle') that was confined to only one, the left or the right, hemifield. Similar to previous studies (Conci et al., 2009, 2018; Mattingley et al., 1997), and as depicted in Fig. 2B, a complete illusory Kanizsa diamond integrated all displayed quarter segments into a single, coherent object. In the ungrouped configuration, the individual cut-out segments were not linked into a corresponding bilateral grouping. We expected to replicate previous findings, namely, that extinction behavior would be less severe when bilateral stimulus configurations could be grouped to elicit the perception of a salient, diamond-like Kanizsa figure compared to ungrouped configurations. In the left- and right-triangle configurations, by contrast, a Kanizsa figure, giving rise to a salient triangle grouping, was presented only within one half of the display, that is: this grouping was not connected with the quarter-segment in the opposite display half. Importantly, the triangle groupings always proceeded from the central midline, thus confining grouping of a salient shape to either the intact, attended (left) or to the impaired, unattended (right) hemispace. This distinguishes the present grouping variations from the square configurations used in the previous studies (see Fig. 1). Accordingly, comparison between these two conditions permitted us to test the efficiency of *hemifield-specific* grouping and its associated attention-attracting effect in neglect/extinction patients. The condition of major theoretical interest in this respect is that with a Kanizsa triangle in the unattended, left hemifield This condition makes it possible to test whether the presence of a salient grouping within the impaired hemispace can improve the detection of a contralesional target—in particular, when attention is engaged in processing an additional target in the ipsilesional, that is, attended hemispace.

2. Materials and methods

2.1. *Participants*

Eleven patients (eight males, $M = 64.5$ years, $SD = 8.29$, range = 53–73 years), recruited from the Neurological Rehabilitation Clinic in Bad Feilnbach, Germany, took part in the experiment. Ten of the patients suffered from a stroke and one from a craniocerebral injury. Inclusion criteria for participation in the experiment were clinical signs of visual hemi-neglect according to the neurological examination and the reports of the patient's neuropsychological therapists, and impaired performance on a minimum of two out of the six neglect subtests of the Behavioral Inattention Test (BIT; Wilson, Cockburn, & Halligan, 1987). BIT sum scores were

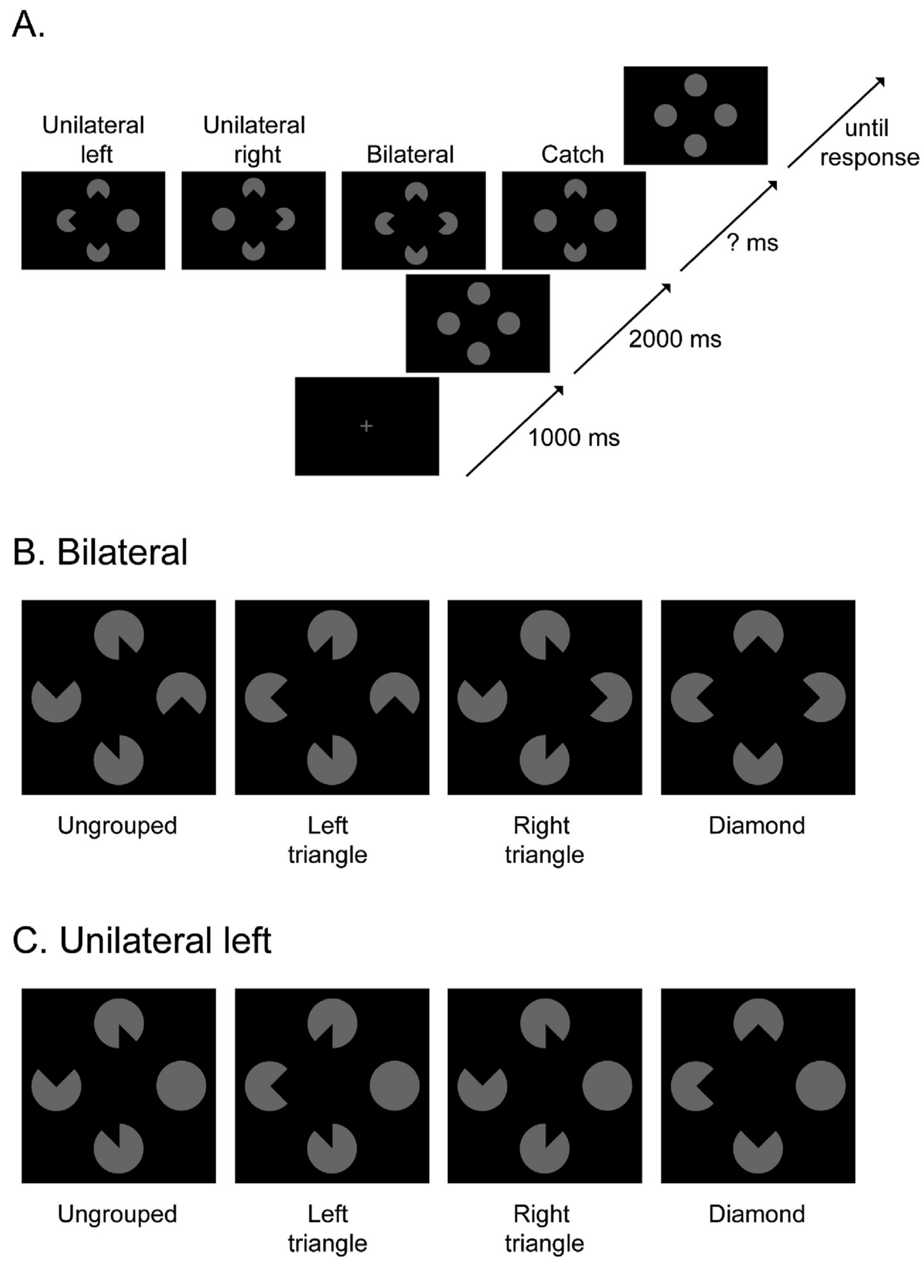


Fig. 2 – (A) Example trial sequence. Each trial started with the presentation of a fixation cross for 1000 ms, followed by a pre-mask display shown for 2000 ms. Next, a Kanizsa-type configuration was presented with removed quarter segments from the top and bottom, and from either the left side, the right side, both sides, or no side (with presentation times adjusted individually for each observer). Finally, a post-mask display was presented until a response was given. (B) Examples of the different types of object groupings presented in bilateral target displays (i.e., displays containing target cut-out segments in both hemifields): In the diamond configuration, a complete illusory figure was induced (right panel). The right triangle condition (middle-right panel) presented an illusory triangle in the right hemifield, and the left triangle condition (middle-left panel) an illusory triangle in the left hemifield. The ungrouped configuration (left panel), which did not induce any illusory figure, served as a baseline. (C) Corresponding examples of the various types of object groupings in unilateral left target displays, in which a cut-out *target* segment was presented only in the left hemifield. Note, that examples of all object groupings for all four types of target displays (i.e., also for all variants of unilateral right and catch displays) can be found in the Supplement.

computed for each patient. Based on these scores, the neglect was rated severe to moderate in four patients (BIT score < 100), mild in three patients (BIT score > 100), and only residual in four patients who scored above the BIT cut-off criteria of 129 at the time of testing. The patients were tested within 4–32 weeks post-injury. In all but two patients, intelligence quotient (IQ) scores were estimated using the German Multiple-Choice Vocabulary Test (Mehrfachwahl-Wortschatz-

Intelligenztest, MWT-B; Lehrl, 2005) and found to be in the normal range. In two patients, an assessment of the IQ scores was not possible because they were either non-native German speakers or had problems to concentrate on the IQ test after having been tested for ~1.5 h in the formal experiment. All participants, however, fully understood the instructions and the experimental procedure. Table 1 summarizes the clinical and demographic data of all patients.

Lesion locations were identified by means of perfusion computer tomography (CT), which was recorded 4–32 weeks after the acquired brain damage and prior to testing. Lesions were mainly confined to the right hemisphere and clustered in inferior-parietal and/or temporo-parietal areas (see Fig. 3). Note that a CT scan was not available from one patient (J.W.), but according to the medical reports from the acute clinic, J.W. actually showed neglect-typical right-parietal lesions as displayed in Fig. 3.

The experimental procedure was approved by the local ethics committee (Faculty of Psychology & Pedagogics, Ludwig-Maximilians-University, Munich), and written informed consent according to the Declaration of Helsinki was obtained from all participants. Our sample size was based on previous, related work and comparable to our previous studies (Conci et al., 2009, 2018). In fact, the sample of neglect/extinction patients was larger than the samples in the majority of the neuropsychological studies on perceptual grouping cited in this article.

2.2. *Apparatus and stimuli*

The experiment was programmed using the Psychophysics toolbox (Kleiner, Brainard, & Pelli, 2007) in combination with Matlab (MATLAB, 2017). During the experiment, the head of the participant was stabilized by a forehead and chin rest, positioned approximately 57 cm from a 17-inch monitor (1024 × 768 pixels screen resolution, 70-Hz refresh rate). Eye movements were monitored by the experimenter using a light-sensitive web-camera. Whenever the patient lost central fixation, the experimenter verbally instructed the participant to re-fixate the screen center. Neglect/extinction patients often show a tendency to overtly shift their eye gaze towards the unimpaired visual field, and this control procedure was intended to minimize these types of eye movements. The experiment was conducted in a sound-attenuated room that was dimly lit.

Stimuli consisted of four gray placeholder disks (3.81 cd/m2), each of a diameter of 1° of visual angle, which were presented against a black background (.01 cd/m2). The disks were arranged in diamond form subtending 3.5° × 3.5°, and their distance from the central fixation cross was 1.3°. There were four different types of target display: *unilateral* left displays consisted of two central disks (one above and one below fixation) and the disk to the left of fixation, which all had a segment cut out whereas the right disk was complete (i.e., without cut-out section); in *unilateral* right displays, segments were removed from the right and the central disks, and the left disk was complete. In *bilateral* displays, all four circles were presented with cut-out (quarter) segments. Finally, in catch trials, only the central (i.e., the top and bottom) disks had cut-out sections, whereas the left and right disks were both complete. Note that catch trials were presented to obtain a measure for guessing. Examples of all four types of target display are depicted in Fig. 2A.

For each of these types of target display, four object grouping variants were generated through systematic changes of the orientation and size of the cut-out segments (see Fig. 2B for examples of these types of object groupings in bilateral target displays). For the diamond configuration (Fig. 2B, right), the segmented disks were arranged such that a complete Kanizsa-type illusory diamond emerged across both hemifields from the inward-facing indents in the disks (Chen, Glasauer, Müller, & Conci, 2018). In addition, two variants of this configuration presented a complete Kanizsa-type illusory triangle, either in the right hemifield (right triangle, Fig. 2B, middle-right), or in the left hemifield (left triangle, Fig. 2B, middle-left). Note that the cutout segment in the other hemifield was presented such that it did not integrate with the triangle, facing randomly either to the top or bottom. Finally, ungrouped configurations were arranged pseudo-randomly such that no illusory figure emerged within the left or the right hemifield: the disks with missing quarter-segments on the left and right faced up and down, and the cut-out segments in the top and bottom disks faced to the left and right, respectively (see Fig. 2B, left).

Table 1 – Clinical and demographic data of the patients.

	Sex	Age	Handedness	Injury type	IQ score	BIT score	TSI (weeks)	Presentation time (ms)
Patients								
J.W.	m	73	r	MCA	94	97	15	650
G.F.	f	64	r	MCA	104	141	7	250
T.C.	m	73	r	MCA	94	91	4	500
H.U.	m	71	r	MCA	94	141	7	15
M.S.	f	53	r	MCA	81	128	5	900
R.L.	f	71	r	MCA	–	139	6	300
J.B.	m	61	r	MCA	–	112	9	200
E.B.	m	54	r	MCA	101	40	32	1000
R.B.	m	53	r	CCI	95	126	19	1500
B.K.	m	73	r	MCA	100	94	4	2000
K.R.	m	64	r	MCA	95	136	12	300

Abbreviations. BIT = behavioral inattention test, CCI = cortical contusion injury, f = female, m = male, MCA = right medial cerebral artery infarction, r = right, TSI = time since injury.

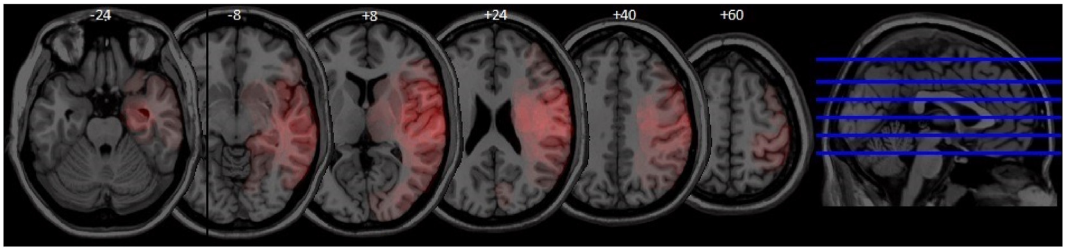


Fig. 3 – Lesion location overlap for N = 10 extinction patients, reconstructed for 6 transversal slices (left) and their positions in sagittal orientation (right). Numbers above the slices depict the z-score in Talairach coordinates. Higher overlaps are shown in darker red.

Of note, the various types of object groupings were always constructed and labeled on the basis of complete, bilateral displays (see Fig. 2B), that is, displays in which all four inducers were presented with cut-out segments. As described above, in unilateral displays, cut-out segments would be presented at the top and bottom positions and on either the left side (unilateral left display) or the right side (unilateral right display) – with the respectively other side containing a full circle. Accordingly, in some configurations, a given grouping would not emerge. For instance, in unilateral left displays, any right triangle grouping would be obstructed or entirely missing (see Fig. 2C), and vice versa for unilateral right displays; even the ‘diamond’ configuration would only be partly rendered in unilateral displays. Thus, perceptual grouping in these variants of the target displays is much weaker (or completely absent), and it therefore does not make sense to interpret grouping-related performance in these (partly) incomplete groupings.

2.3. *Procedure*

Each trial started with the presentation of a fixation cross at the center of the screen for 1000 ms. This was followed by a pre-mask display which presented four complete disks in a diamond arrangement around fixation for 2000 ms. Next, the target display presented one of the four possible object configurations (see some examples of bilateral and unilateral left target displays in Fig. 2B and C, respectively; the full set of all possible stimuli is provided in the Supplement). In the target display, segments were removed from the top and the bottom and from either the left side, the right side, both sides, or from neither left nor right side (see Fig. 2A). Thus, zero to two segments were removed from the left and right circles and these served as the to-be-detected *targets*, whereas the two segments on the top and bottom were response-irrelevant *distractors*. Exposure times of the target display were adjusted individually for each observer based on the results of a pre-test (see details below). Finally, a post-mask display again presented four complete circles until the patient gave a verbal response to indicate on which side(s) a segment was removed from the target display (four alternatives: left, right, both, or none). The experimenter recorded the answers via keyboard press. Each trial was separated from the next by a blank screen with the central fixation cross, which was shown for 1000 ms. Fig. 2A presents an example trial sequence and the possible target displays, illustrating where the cutoff segments could be removed from a given configuration.

Prior to the experiment proper, each patient completed a pre-test that was comparable to the procedure used in previous studies (e.g., Conci et al., 2018). The aim of this pre-test was to determine the individual target display duration at which unilateral left targets could be detected with an accuracy of approximately 75%. The pre-test also served as a practice run to ensure that the instructions were fully understood. The display sequence in the pre-test was identical to the actual experiment, except that only ungrouped configurations were presented. The duration of the target display was determined using an adaptive staircase procedure with a starting duration of 200 ms, which was adjusted individually until the performance criterion (~75% correct detection of unilateral left targets) was reached. Presentation durations were estimated on the basis of 20 randomized trials (with 10, 5, 3, and 2 trials presenting unilateral left, unilateral right, bilateral, and catch-trial target displays, respectively). The unilateral left target displays were used to estimate the presentation duration of the displays in the main experiment. The mean presentation duration derived from this pretest was 731.5 ms (individual values for each patient are listed in Table 1), which is roughly comparable to a previous, related study (Conci et al., 2018).

The experiment itself consisted of 288 experimental trials, which were presented in eight blocks of 36 trials each, with a break after each block. The length of these breaks was determined by the patients themselves. Each block consisted of 8 unilateral left, 8 unilateral right, 16 bilateral, and 4 catch trials, which were presented in a randomized order. The various types of object configuration (ungrouped, left triangle, right triangle, or diamond) were presented in randomized order across the whole experiment. In summary, the experiment varied two factors, object configuration (ungrouped, left triangle, right triangle, or diamond) and target (unilateral left, unilateral right, bilateral, catch).

3. Results

3.1. *Detection accuracies*

Statistical analyses were performed using repeated-measures analyses of variance (ANOVAs) and subsequent post-hoc tests (paired-samples *t*-tests with Holm correction for multiple comparisons) with the program R Studio (RStudio Team, 2015). Our analysis approach was three-staged. An initial analysis was performed to provide an overview of the basic level of performance for the various types of configuration in unilateral right target displays, that is, displays with a single target presented in the intact (attended) hemifield. Next, we compared the various configurations in catch trials (i.e., trials without targets but with varying distractors), in order to gauge the level of guessing on the target trials. Third, of major theoretical interest, we quantified performance in the impaired, left hemispace in order to examine for object integration under conditions of inattention. This latter analysis of the left hemispace involved several comparisons that compared the various object configurations in unilateral left and bilateral target displays.

First, performance for unilateral targets in the right, unimpaired hemispace turned out very accurate overall (89.9% correct 'right' detections). A repeated-measures ANOVA of the mean detection accuracies for unilateral right targets, with the single factor object configuration (ungrouped, left triangle, right triangle, diamond), yielded a significant main effect, F (3, 30) = 4.07, p = .015, $\eta 2$ = .19 (see Fig. 4A). Holm *post-hoc* tests, however, failed to revealed any significant differences among the various configurations (ungrouped: 92.6%, left triangle: 87.4%, right triangle: 97.2%, diamond: 82.2%), all t (10)'s < 2.92, all p's > .05. This is likely owing to the familywise error correction for multiple comparisons that we used: without Holm correction, the diamond configuration depicted a less accurate performance compared to the ungrouped and right triangle configurations, both t (10)'s > 2.46, both p's < .05 (see Fig. 4A). The somewhat elevated error rates with the diamond configuration might have occurred because the patients tended to respond to the incomplete (unilateral right) diamond as if it were complete, that is, as if there was a target not only on the right but also the left side.

Second, the overall performance on catch trials showed that the participants' accuracy was also high for displays that did not contain a target (88.8% correct 'none' responses). An ANOVA of catch-trial performance comparable to that above also revealed a significant main effect of object configuration, F (3, 30) = 4.18, p = .013, $\eta 2$ = .11. However, again, Holm post-hoc comparisons failed to reveal any significant differences among the various configurations (ungrouped: 88.6%, left triangle: 88%, right triangle: 80.7%, diamond: 97.7%), all t (10)'s < 2.78, all p's > .05. Without such a familywise error correction, performance was significantly more accurate with the diamond configuration compared to the other three configurations, all t (10)'s > 2.39, all p's < .05 – suggesting that the symmetric distractors at the top and bottom of the diamond configuration facilitated responding "none" to some extent (see example stimuli in the Supplement). Overall, though, the catch-trial accuracies show that participants were able to perform the task without any indication of undue guessing responses.

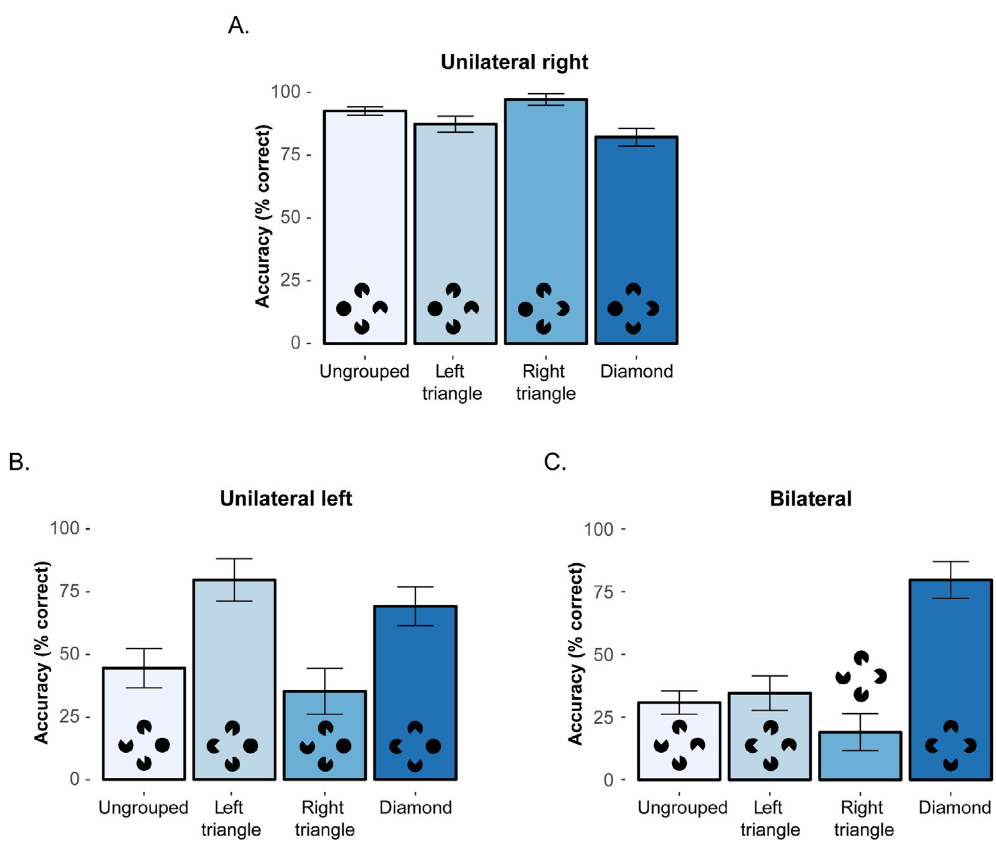


Fig. 4 – Mean percentages of correct detections (and associated within-subject 95% confidence intervals) as a function of object configuration (ungrouped, left triangle, right triangle, diamond) for (A) unilateral right target displays, (B) unilateral left target displays, and (C) bilateral target displays.

Following these preliminary analyses, we assessed performance for the impaired hemispace by computing a repeated-measures ANOVA on the detection accuracies with the factors target (unilateral left, bilateral) and object configuration.[2] The corresponding mean accuracies per condition are depicted in Fig. 4B and C. This analysis revealed a significant (Greenhouse-Geisser corrected) main effect of object configuration, F (1.47, 14.7) = 38.30, $p < .001$, $\eta 2 = .44$, with performance varying overall for the various object types (ungrouped: 37.6%, left triangle: 57.1%, right triangle: 27.1%, diamond: 74.4%). While there was no significant main effect of target, F (1, 10) = 4.11, $p = .701$, importantly, the 2-way interaction was significant, F (3, 30) = 15.77, $p < .001$, $\eta 2 = .19$.

To decompose the interaction, follow-up analyses were performed separately for the two types of target. First, for unilateral left targets (mean correct detections: 57.1%), the main effect of object configuration was significant, F (3, 30) = 17.97, $p < .001$, $\eta 2 = .36$ (see Fig. 4B). Holm *post-hoc* tests revealed detection accuracies to be significantly higher for the left triangle (79.6%) and diamond (69.1%) configurations as compared to the right triangle (35.2%) and ungrouped (44.4%) configurations, all t (10)'s > 3.34, all p's < .023. Detection accuracies were comparable both between diamond and left triangle configurations, t (10) = 1.92, $p = .168$, and between right triangle and ungrouped configurations, t (10) = 1.52, $p = .168$. Together, this pattern of results indicates that with unilateral left displays, the emergence of a salient object grouping in the left hemifield (in left triangle and diamond configurations) substantially facilitated the rate of target detection.

Second, for the various bilateral target conditions, that is, displays that would typically lead to a pattern of extinction (Fig. 4C; mean correct detections: 41%), again, the main effect of object configuration was significant, F (3, 30) = 45.73, $p < .001$, $\eta 2 = .67$. Holm *post-hoc* tests revealed accuracy to be higher for the diamond configuration (79.7%) compared to all other configurations (left triangle: 34.5%, t (10) = −8.05; right triangle: 19.0%, t (10) = −9.22; ungrouped: 30.8%, t (10) = −9.28; all p's < .001), whereas there were no differences among the latter (all $p > .05$). This pattern indicates that with bilateral displays, a given grouped object reduces extinction effectively only when the respective to-be-completed parts extend across both the impaired and the attended hemispaces (i.e., in the diamond configuration). By contrast, salient groupings that are confined to the impaired hemispace (i.e., the left triangle configuration) fail to produce a comparable increase in performance for detecting bilateral cut-off segments.

In a further analysis, we directly compared the detection accuracies for the various object configurations between unilateral left and bilateral displays, in order to determine particular configurations that depend on the availability of attentional resources. *Post-hoc* comparisons showed that the accuracies did not differ significantly between unilateral left and bilateral displays for ungrouped (44.5% vs. 30.8%), right triangle (35.2% vs. 19.0%), and diamond (69.1% vs. 79.7%) configurations (all t (10)'s < 2.87, all p's > .05). Thus, in both unilateral left and bilateral displays, the left target could be detected quite accurately when a salient grouping was presented in the entire visual field (in the diamond configuration). Conversely, with both unilateral left and bilateral displays, performance was relatively inaccurate when there was no grouping (in the ungrouped configuration), or when there was a grouping that was confined to the intact (right) hemispace (in the right triangle configuration). However, only in the case of the left triangle configuration did participants detect the left target significantly better when it was presented in unilateral left displays (79.6%) as compared to bilateral displays (35.5%), t (10) = 4.51, $p = .021$. This means there is a reliable accuracy benefit for grouped objects in the impaired, unattended hemispace, provided that the grouped object is presented unilaterally. But the benefit deriving from grouping is abolished when attention is unavailable, that is, when another (non-grouping) target needs to be processed in the intact, attended hemispace.

Of note, participants only achieved 44.5% correct responses for the ungrouped configuration in unilateral left target displays, even though prior to the formal experiment (in the pretest), we ensured that unilateral left targets could be detected with an accuracy of approximately 75% (see Methods section). This drop of performance from the pretest to the actual experiment was somewhat unexpected, given that previous studies employing a comparable procedure reported a relatively high level of performance throughout the entire experiment (Mattingley et al., 1997; Conci et al., 2009, 2018). A potential explanation for this decline in accuracy might relate to the increase in task difficulty in the current experiment. For instance, the diamond-shaped layout of the search display not only presented lateral targets, but also target-similar (yet task-irrelevant) distractors at the top and bottom disk locations in each object configuration (see Fig. 2A). Presenting these additional distractors in the display might have harmed processing of the target items in particular in our extinction patients who, by definition, have problems in detecting a target among multiple other stimuli. Moreover, unlike previous comparable studies, the current experiment did not present the various configurations in separate blocks, but in randomized order across trials, thus making it more difficult for the patients to prepare for a given, specific display. Together, these two changes in the paradigm might explain the observed reduction in performance as the experiment progressed, and this increase in difficulty might in turn explain why contralesional groupings (in the left display half) modulated response accuracy even though there was no ipsilesional stimulus that would have led to extinction behavior.

3.2. *Types of response errors*

A final analysis was performed to quantify the specific types of response errors that were made for the various object configurations in displays with a target in the impaired, left hemispace (in unilateral left and bilateral target displays).

[2] It should be noted that previous studies (e.g., Mattingley et al., 1997) sometimes computed "left detections" to quantify performance in particular in the impaired hemispace. Here, we instead quantified the overall mean detection accuracies (which would, in bilateral displays, only count the detection of both the left and right hemifield target as a correct response). However, analogous analyses performed on such a 'left detection' measure in the current experiment revealed exactly the same pattern of results as reported here for the overall (% correct) accuracy data.

That is, we systematically analyzed the distribution of errors across the various possible incorrect responses for a given target display, in order to determine—in addition to the above analyses—which specific response was predominant for a given type of configuration. First, error probabilities for unilateral left targets were analyzed using a repeated-measures ANOVA with the factor response (right, both, none) and object configuration (ungrouped, left triangle, right triangle, diamond). Note that the correct response to unilateral left displays would be "left", hence the three analyzed response alternatives were all incorrect. This analysis revealed a significant main effect of response, F (1.04, 10.4) = 15.20, $p < .001$, $\eta2 = .42$: while the participants produced only few false alarms in erroneously reporting a right visual field target (erroneous response "right": 5.8%, "both": 2.6%), they were much more likely to miss the left visual field target (response "none": 33.4%). In addition, there was also a significant effect of object configuration, F (3, 30) = 17.04, $p < .001$, $\eta2 = .11$, which essentially mirrored the above-reported result, namely, overall more errors for right triangle (21%) and ungrouped (17.8%) configurations than for left triangle (6.8%) and diamond (10%) configurations. Importantly, the 2-way interaction turned out to be significant, too, F (2.20, 22.02) = 5.91, $p = .007$, $\eta2 = .14$.

To disentangle the significant interaction (see Fig. 5A), follow-on analyses were performed separately for the three types of error responses and for each configuration. First, for the (erroneous) response "right", pairwise comparisons revealed no significant difference across ungrouped, left triangle, right triangle, and diamond configurations (all t (10)'s < 2.00, all p's > .05). There were also no differences for the (erroneous) response "both" (all t (10)'s < 1.64, p's > .05). For "none" responses, by contrast, the error probability was significantly higher for ungrouped (49.4%) and right triangle (44.3%) configurations as compared to left triangle (18.2%) and diamond (21.6%) configurations (all t (10)'s > 3.07, all p's < .035); between the former two and the latter two configurations, the error rates were comparable (all t (10)'s < 1.27, all p's > .05). This pattern shows that in unilateral left target displays, participants were better in detecting the target if it was part of a salient object grouping (in left triangle and diamond configurations) – thus mirroring the results as reported above for the detection accuracies.

Second, for bilateral target displays, the error probabilities were again analyzed by a repeated-measures ANOVA with the factors (erroneous) response (left, right, none) and object configuration. This analysis yielded significant main effects of response, F (1.22, 12.16) = 47.40, $p < .001$, $\eta2 = .70$, and object configuration, F (3, 30) = 41.01, $p < .001$, $\eta2 = .24$. The response effect confirmed that the patients indeed suffered from visual extinction, since the predominant error response for all bilateral displays was "right", (erroneous response "right": 46.8%, "left": 8.9%, "none": 1.6%; all t (10)'s > 2.98, all p's < .001; "right" responses were more frequent than "left" or "none" responses). The effect of object configuration again reflected the finding (already seen above) of errors being reduced overall only for the (fully grouped) diamond configuration (6.7%), but not for the other three types of configuration (ungrouped: 22.5%, left triangle: 21.1%, right triangle: 25.9%). In addition to the two main effects, the interaction was also again significant, F (2.23, 22.32) = 18.86, $p < .001$, $\eta2 = .36$.

Decomposing this interaction (see Fig. 5B) by pairwise comparisons showed that erroneous "left" and "none" responses were relatively infrequent and not statistically different across all four configurations, all t (10)'s < 2.55, all p's > .05. However, erroneous "right" responses (which, with bilateral target displays, reflect typical extinction behavior) occurred significantly more often with right triangle configurations (71.3%) than with ungrouped configurations (55.9%), t (10) = 3.12, $p = .022$. Erroneous "right" responses again also occurred more often than with left triangle configurations (44.9%), t (10) = −2.32, $p = .043$. Finally, the diamond configurations (15.1%) elicited relatively few erroneous "right" responses compared to each of the other three configurations, all t (10)'s > 6.12, all p's < .001. This gradual variation of performance essentially shows that the benefit of grouping is

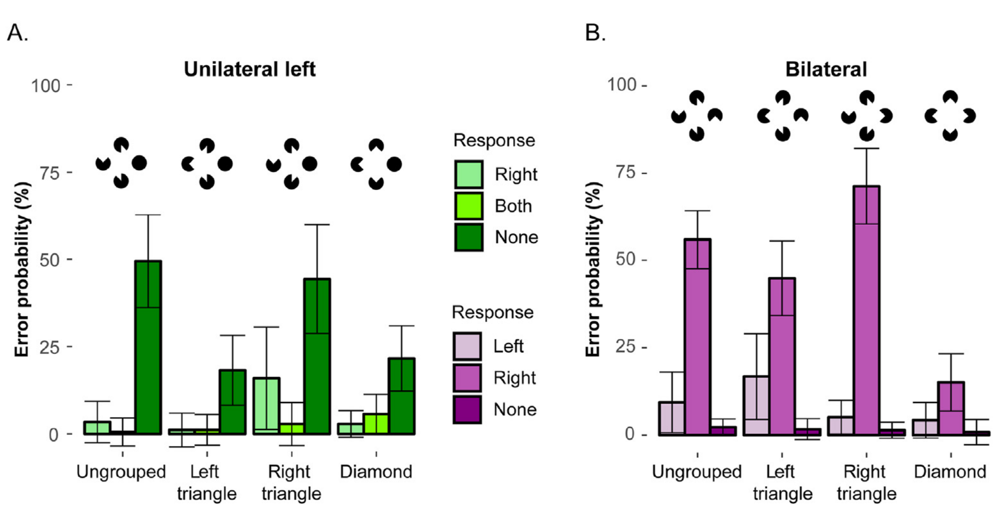


Fig. 5 – Types of response errors (and associated within-subject 95% confidence intervals) as a function of object configuration (ungrouped, left triangle, right triangle, diamond) for (A) unilateral left target displays and (B) bilateral target displays.

linked to the availability of attentional resources: the presence of a grouping that links both hemifields (diamond configuration) is most effective in reducing extinction, whereas a salient grouping that is, however, confined to the unattended hemispace (left triangle configuration) can ameliorate extinction only to a certain extent (relative to the ungrouped configurations). However, when the salient grouping is confined to the attended hemispace (right triangle grouping), then the non-salient target in the unattended hemispace is rather unlikely to be detected. This shows that the effectiveness of the grouping to capture attention depends on the availability of attentional resources in the first place.

4. Discussion

The present study investigated how perceptual grouping interacts with the allocation of selective attention. To this end, we compared object integration processes in the attended and in the unattended (i.e., impaired) hemispace of neglect patients with right-hemispheric, parietal brain lesions and associated inattention towards stimuli in the left visual hemifield. Importantly, limiting perceptual grouping operations to only one hemifield prevented the cross-hemispheric spreading of attention, which might have occurred concurrently with the integration of a grouped object. In our experiment, the patients were asked to detect lateral targets while the presented display items systematically varied in terms of grouping such that individual parts could be integrated into coherent Kanizsa-type illusory figures within the left, within the right, or across both visual hemifields. Thus, this setup permitted preattentive grouping to be disentangled from a spreading of attention into the impaired hemispace along the grouped object. Given this, our design allowed us to determine whether (i) attention is required in the first place to bind fragmentary parts into a coherent whole, and (ii) whether the formation of an integrated object can in turn act like a saliency signal that summons attentional resources.

The results showed that when individual segments were not grouped across both hemifields, detection of bilateral targets was compromised: the patients missed a high proportion of targets on the left side, which is a tell-tale sign of extinction. By contrast, when target segments were grouped to form a single coherent diamond shape, performance improved substantially (by ~49%); that is, targets on the left side were detected more frequently, showing that the completion of a coherent object reduces extinction in the impaired hemispace (consistent with Mattingley et al., 1997, and Conci et al., 2009). Similar findings of preserved access to complete objects despite severe inattention in one half of the display have previously been taken to support the view that attention is essentially object-based, that is, the integration of parts into whole objects precedes the allocation of attention (see Driver & Baylis, 1998; Humphreys, 2016; Scholl, 2001, for reviews). Attentional spreading within the boundaries of the grouped (diamond) object could then explain why the two, left- and right side targets are detected more efficiently compared to when the two targets are presented at the same lateral positions, but not within a single, integrated object (e.g., in ungrouped displays). In the latter case, attentional spreading would not be promoted by the presented structure of object elements (see Egly, Driver, & Rafal, 1994; and Chen, 2012, for a review of findings from object-based attention).

Critically, however, our results also show that a substantial reduction of extinction in bilateral displays by means of grouping was observed *only* when the object extended across both hemifields (allowing for attentional spreading to occur). In particular, completion of a salient triangle configuration within the impaired, unattended hemispace facilitated detection of a left-sided target in bilateral configurations only to a small extent. That is, processing of a task-relevant but non-salient single target item in the intact visual hemispace did hamper target detection in the impaired, unattended hemispace—despite the left side of the display consisting of a salient illusory figure. Of note, such salient object groupings have previously been found to capture attention in healthy participants (see e.g., Kimchi et al., 2016; Rauschenberger & Yantis, 2001; Senkowski et al., 2005; Wiegand et al., 2015), that is: the groupings (formed at preattentive coding stages) were interpreted as giving rise to bottom-up saliency signals that summon attention even when task-irrelevant. However, this interpretation would be inconsistent with the present results in neglect patients, which show that grouped objects do not capture attention when attention is currently engaged elsewhere.

Importantly, our design allowed more experimental control over the exact size of the unilateral Kanizsa figure compared to the previous studies of Conci et al. (2009; 2018). With their displays, the partial groupings from one hemifield were assumed to propagate into the other hemifield (see Fig. 1 for example configurations). While this is so phenomenally, how far the surface covered by the illusory object did extend into the other hemifield might have been quite variable since the spatial distribution of extinction/neglect is relative rather than absolute (e.g., Bays et al., 2010). In the current design, by contrast, the (unilateral) triangle's vertical border was delineated by the boundary induced by the cut-out sections of the upper and lower disks on the central midline—so that the illusory object was confined to only one hemifield, without extending into the other hemifield. Our results thus add support to the proposal that a grouped object reduces extinction effectively only when the respective to-be-completed parts extend across both the impaired and the attended hemispace (Conci et al., 2018). Consistent with these findings from extinction patients, studies that presented near-threshold stimulus configurations in masked-priming paradigms (Schwarzkopf & Rees, 2011) or that presented groupings under conditions of inattentional blindness (Mack, Tang, Tuma, Kahn, & Rock, 1992) have also suggested that attention plays a crucial role for successful perceptual grouping.

In unilateral left displays, we found that left-sided targets were detected significantly better when the cut-out sections were arranged such that an illusory figure could emerge within the left visual hemifield, compared to when the left display half contained an ungrouped element arrangement. That is, the patients still tended to miss the left-sided target more often in ungrouped and right triangle configurations than in diamond and left triangle configurations. Thus, patients with visual hemi-neglect seem to be able to group separate parts into coherent whole objects even when presented in the left, unattended hemispace. This process, however, is foiled whenever a second, task-relevant target is presented in the attended hemispace. The lack of a task-relevant target in the attended visual field therefore allows attentional resources to reorient from the attended, right hemispace into the neglected, left hemispace. Such reorienting of attention in turn triggers completion of the shape (e.g., in left triangle or diamond configurations), with the integrated shape in turn increasing the saliency of the left-sided target, thereby enhancing its detectability. This shows that neglect is ameliorated by salient object groupings—but, importantly, this benefit is conferred only when attention is available. In general agreement with this finding, previous studies have reported that grouping can increase the conspicuity of a Kanizsa-type target, thereby enhancing search efficiency (Conci, Müller & Elliot, 2007; Conci, Töllner, Leszczynski, & Müller, 2011; Nie, Maurer, Müller, & Conci, 2016; Wiegand et al., 2015).

In summary, our results further support the idea that attention is necessary for successful object integration (e.g., Conci et al., 2018). Accordingly, guidance of attention by grouped objects is not possible without attending to the to-be-grouped objects in the first place. This result pattern may, for instance, be explained within the framework of the reverse hierarchy theory (Hochstein & Ahissar, 2002). In this view, the individual inducer elements (the circles with missing segments) would undergo some basic, "preattentive" processing in an initial feedforward sweep of processing. Selective attention is in turn engaged subsequently and triggers perceptual grouping via recurrent feedback from higher to lower levels of processing in the visual hierarchy. That is, an integrated object could guide attention only after some attention-dependent grouping has generated a complete-object representation. This implies that object completion can be successful when sufficient attentional resources are deployed to those parts of the visual field that could give rise to the perception of an integrated object, but not when the allocation of attention towards these grouping-inducing elements is prevented (e.g., by a task-relevant target that is presented elsewhere). Overall, this suggests that attention may indeed act like a "glue" to bind parts into wholes (Conci et al., 2018), contrary to the predominant view advocated in several of the above-mentioned studies. The attention-dependent integration of image elements has previously been referred to in terms of "incremental grouping" (Roelfsema, 2006; Roelfsema & Houtkamp, 2011), which appears to reflect a time-consuming and capacity-limited process that requires the gradual spread of attention across the representation of an object. This spreading along the boundaries of an object would in turn establish an object-based representation that is available for higher-order processing.

Author contributions

LN collected data, analyzed data, and wrote the paper. KF designed the experiment and critically revised the manuscript. ALB collected data and critically revised the manuscript. IG recruited participants, examined medical records, confirmed diagnostic status of participants, and created the lesion mapping figure. HJM critically revised the manuscript. MC designed the experiment, supervised data collection, wrote and critically revised the manuscript. All authors read and approved the final manuscript.

Open practices

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in this study. No part of the study procedures or analyses were pre-registered prior to the research being conducted. However, all relevant study materials, data, and analysis code are available on the Open Science Framework following this link: https://osf.io/thba7/.

The study in this article earned Open Materials and Open Data badges for transparent practices. Materials and data for the study are available at https://osf.io/thba7/?view_only=3df9262964034997821040bfd1fe7294.

Declaration of competing interest

The authors declare that they have no competing interests.

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Supplementary data

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2.2. CHANGES IN ATTENTIONAL BREADTH SCALE WITH THE DEMANDS OF KANIZSA-FIGURE OBJECT COMPLETION – EVIDENCE FROM PUPILLOMETRY

The author of this dissertation designed and programmed the experiment, collected and analyzed the data, created plots and interpreted the results, and wrote the manuscript. Hermann J. Müller commented on and critically revised the manuscript. Markus Conci helped to design and supervise the experiment. He also contributed to the interpretation of the results and critically revised the manuscript.

Changes in attentional breadth scale with the demands of Kanizsa-figure object completion – evidence from pupillometry

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Abstract

The present study investigated whether the integration of separate parts into a whole-object representation varies with the amount of available attentional resources. To this end, two experiments were performed, which required observers to maintain central fixation while searching in peripheral vision for a target among various distractor configurations. The target could either be a "grouped" whole-object Kanizsa figure, or an "ungrouped" configuration of identical figural parts, but which do not support object completion processes to the same extent. In the experiments, accuracies and changes in pupil size were assessed, with the latter reflecting a marker of the covert allocation of attention in the periphery. Experiment 1 revealed a performance benefit for grouped (relative to ungrouped) targets, which increased with decreasing distance from fixation. By contrast, search for ungrouped targets was comparably poor in accuracy without revealing any eccentricity-dependent variation. Moreover, measures of pupillary dilation mirrored this eccentricity-dependent advantage in localizing grouped targets. Next, in Experiment 2, an additional attention-demanding foveal task was introduced in order to further reduce the availability of attentional resources for the peripheral detection task. This additional task hampered performance overall, alongside with corresponding pupil size changes. However, there was still a substantial benefit for grouped over ungrouped targets in both the behavioral and pupillometric data. This shows that perceptual grouping scales with the allocation of attention even when only residual attentional resources are available to trigger the representation of a complete (target) object, thus illustrating that object completion operates in the "near absence" of attention.

Keywords: perceptual grouping, object integration, visual attention, pupillometry, covert attention, attentional breath

1. Introduction

The visual system has developed dedicated mechanisms that structure and organize the complex visual input that we are constantly exposed to in everyday life. One such mechanism, serving the integration of fragmented image parts into coherent, whole "objects", is perceptual grouping. Implementing a set of organizational principles, grouping processes structure the perceptual input, combining fragments into coherent wholes and segmenting objects from each other as well as the background (Koffka, 1935; Wertheimer, 1923). One example that illustrates these mechanisms of object integration is the so-called Kanizsa figure (Kanizsa, 1976) – see Figure 1A for an example. In this configuration, the arrangement of the circular "pacman" inducer elements creates the vivid impression of an "illusory" rectangle that lacks a corresponding physical object.

Object integration by means of perceptual grouping appears to be achieved in a fairly effortless manner. However, whether object completion operates automatically or whether it depends on the engagement of attention is a matter of intense debate. Influential accounts such as Feature Integration Theory (Treisman & Gelade, 1980) assume that attention must first be allocated to a given stimulus in order to enable part-to-whole integration and render complete-object representations. In this view, perceptual grouping would generate a coherent whole object only when focal attention is allocated to the object's location. Opposing theories posit that the representation of complete objects arises "preattentively", prior to the engagement of attention (Driver & Baylis, 1998; Humphreys, Romani, Olson, Riddoch, & Duncan, 1994; Scholl, 2001). Major support for the latter, "object-based" view of attention comes from studies that tested object-completion mechanisms in neuropsychological patients with parietal brain damage and associated deficits of selective attention in one side of the visual field. While these patients would typically miss targets in the impaired visual field, access to such "neglected" targets can be substantially improved by providing a grouped structure that links the attended with the unattended region across the two visual hemifields (e.g., Mattingley, Davis, & Driver, 1997; Conci, Böbel, Matthias, Keller, Müller, & Finke, 2009). Importantly, however, our recent studies show that such a benefit for grouped objects depends crucially on the availability of attention: these patients exhibited enhanced target detection in the impaired hemifield only when attention was available to spread into the impaired visual field, but not when it was engaged in the unimpaired visual field (Nowack, Finke, Biel, Keller, Müller, & Conci, 2021; Gögler, Finke, Keller, Müller, & Conci, 2016; Conci, Groß, Keller, Müller, & Finke, 2018). This in turn supports the view that object completion requires the availability of at least some, residual amount of attentional resources.

Following these findings from neuropsychological patient studies, the present experiments investigated whether part-to-whole object integration and search guidance by salient, integrated objects would likewise scale with the amount of available attentional resources in healthy participants. Methodologically, our study made use of pupillometry (the measurement of pupil diameter), since variations of pupil size have been shown to also reflect (higher-level) information processing (see for example Eberhardt, Strauch, Hartmann, & Huckauf, 2021), including the allocation of visuo-spatial attention. The latter is evidenced by findings of a close relationship between the pupillary light reflex and concurrent attention shifts (for reviews, see Laeng & Alnaes, 2019; Mathôt, 2018). For instance, covert shifts of attention towards a bright (or, respectively, dark) stimulus in the periphery consistently evoke a pupillary constriction (or, respectively, dilation) – demonstrating that changes in pupil size can be used to track where attention is allocated (Binda, Pereverzeva, & Murray, 2013; Mathôt, van der Linden, Grainger, & Vitu, 2013; Mathôt, Dalmaijer, Grainger, & Van der Stigchel, 2014; Naber, Alvarez, & Nakayama, 2013).

In fact, pupil-size measures may also serve as markers of the allocation of covert attention to peripheral stimuli in the absence of any luminance manipulations, as shown by Brocher, Harbecke, Graf, Memmert, and Hüttermann (2018). In their study, two peripheral stimulus configurations, consisting of four objects each, were presented bilaterally at varying distances from (central) eye fixation (though with both configurations being equidistant from fixation). Observers fixated the screen center and identified the lateral configurations via covert shifts of attention. After the onset of the stimuli, observers were presented with a central arrow cue that pointed towards one side of the display, and their task was to report the number of targets (white triangles) on the cued side. The results revealed performance accuracy to decrease with increasing eccentricity (ranging from 12.5º up to 42.5º). Importantly, the increase in task difficulty with eccentricity was associated with stronger pupil dilations for more peripheral stimuli, suggesting that pupil size reflects covert shifts of attention to the target(s) without any change in luminance (see also Hüttermann & Memmert, 2017; Hüttermann, Memmert, & Simons, 2014; Hüttermann, Memmert, Simons, & Bock, 2013). In a more recent experiment, Ivanov, Lazovic, and Mathôt (2019) also measured changes in pupil size in response to attention shifts. Participants were presented with tilted Gabor patches, three on the left and three on the right side of fixation (at varying eccentricities). Following a bilateral peripheral location cue, observers were asked to indicate the orientation of the two cued "target" Gabor patches (one on each side of the display, with both targets being equidistant from fixation and depicting the same orientation). The results again showed that pupil size increased with increasing eccentricity of the attended locations. These findings consistently show that the pupil size is linked to attentional shifts or, respectively, the “breadth” of attention: the pupil becomes wider when attention is allocated to more peripheral locations, that is, when attention is distributed more broadly across the visual field as compared to when a more central focus is required (Daniels, Nichols, Seifert, & Hock, 2012; Brocher et al., 2018; Ivanov et al., 2019; Mathôt & Ivanov, 2019; Klatt, Noël, & Brocher, 2021; see Mathôt, 2020, for a review;).

Accordingly, in the present study, we also used pupil-dilation measures as a marker for the allocation of visual attention to peripheral stimuli that varied in their demands for object integration. In more detail, we implemented a visual search task that presented variants of Kanizsa figures as target and distractor configurations, roughly comparable to those used in previous studies (Conci, Müller, & Elliott, 2007; Conci, Töllner, Leszczynski, & Müller, 2011; Nie, Maurer, Müller, & Conci, 2016; Nowack et al., 2021; Wiegand, Finke, Töllner, Starman, Müller, & Conci, 2015). Importantly, the target could vary in terms of its grouping strength: it could be either a complete object, namely, an illusory Kanizsa-type rectangle (grouped target, Figure 1A), or a physically identical, symmetrical configuration but without inducing an illusory figure (ungrouped target, Figure 1B). The distractors presented together with the target in the display were non-symmetric arrangements that were equally similar to both types of target (Figure 1C). A given display (Figure 1D) consisted of six candidate target configurations – three to the left and three to the right of the central fixation cross at varying eccentricities (5°, 10°, and 15°). In Experiment 1, participants were required to maintain central fixation and localize the lateral target item, which was positioned randomly at any of the three possible eccentricities in one or the other display half, thus putatively requiring attention to either focus more centrally or to broaden the focus more towards the periphery in order to report the (left/right) hemifield in which the target appeared. In Experiment 2, targets were only displayed at the intermediate (i.e., 10°) position while attention was additionally engaged, at least to some degree, in a second, foveal line-discrimination task (Figure 1E) – comparable to the procedure used in previous studies (e.g., Mack, Tang, Tuma, & Kahn, 1992; see also Li, Van Rullen, Koch, & Perona, 2002; Moore & Egeth, 1997)[1]. The adoption of a foveal attention-demanding task allowed us to further test whether the detection of a grouped versus ungrouped target depends on the amount of attentional resources that are currently available.

[1] Note, that an important difference to the study of Mack et al. (1992) is that the peripheral stimuli in our experiment were task relevant. It could therefore be assumed that a certain (possibly, a rather small) amount of the available attentional resources was still devoted to the peripheral stimuli despite the central task load. By contrast, Mack et al. (1992) only tested processing of an irrelevant stimulus on a single “surprise” trial, thus effectively inducing “inattention”.

Previous search studies with Kanizsa figures showed search efficiency to be higher (Conci et al., 2007; Nie et al., 2016) and attention allocation to be faster for grouped as compared to ungrouped target configurations (Chen, Nie, Müller, & Conci, 2019; Conci et al., 2011; Wiegand et al., 2015) – consistent with attentional guidance improving with an increase of the grouping strength in the target. However, it is not clear whether the allocation of covert attention to a given target at varying distances from fixation, as reflected in pupil-dilation measures, would scale with such target-related grouping demands. Moreover, if attention is engaged to a large extent in a second, foveal task, its allocation to the peripheral target should be hampered by this limitation of attentional resources – which should again be reflected in pupil-dilation measures.

Experiment 1

Experiment 1 used a visual search task to examine whether a narrow or broadly distributed focus of attention influences object integration for grouped versus ungrouped target items at varying eccentricities (of 5º, 10º and 15º). As depicted in Figure 1D, observers were presented with a linear (horizontal) array of six stimulus configurations, three to the left and three to the right of central fixation; their task was to indicate whether one of two possible target configurations appeared on the left or the right side (among the five distractor configurations). Observers were instructed to maintain central fixation throughout a given trial (checked by an eye tracker). Accordingly, correctly (left/right) localizing the target was assumed to require a narrower, or more broadly tuned attentional focus. Both performance-accuracy and pupil-dilation measures (the latter serving as a marker for variations of the attentional breadth; see, e.g., Ivanov et al., 2019) were obtained to determine how object completion affects the processing of the target item in the periphery.

2. Materials and Methods

2.1. Participants

30 participants (10 males; mean age 28.03 [*SD* = 7.22] years) with normal or corrected-to-normal vision took part in the experiment. One participant, however, had to be excluded from the Pupillometry analysis due to problems with the eye-tracker recording. Participants (mainly Psychology students) received either monetary compensation (9 Euro) or course credits for taking part in the experiment. The experimental procedure was approved by the local ethics

committee (Department of Psychology, Ludwig-Maximilians-University Munich), and written informed consent according to the Declaration of Helsinki was obtained from all participants prior to the experiment.

Sample size was determined on the basis of an a-priori power analysis, which aimed for 95% power to detect a minimum $f(U)$ effect size of 0.35 (partial $\eta^2 = .11$) at an alpha level of .05 and a non-sphericity correction of 1. This effect size was determined on the basis of previous studies that used a comparable task and similar stimulus configurations (Nowack et al., 2021; Conci et al., 2018). An influence of attention on object integration (in a within-subjects design) would be reflected by a significant 2-way Target Configuration by Eccentricity interaction, which, according to our power analysis, would require N=16 participants. However, pupil size effects are typically rather small and previous pupillometry studies therefore typically used larger sample sizes (see for example Brocher et al., 2018; Ivanov et al., 2019). Given this, we decided to almost double the sample size and to test a total of N=30 participants.

2.2. Apparatus

The experiment was programmed with the Psychophysics and Eyelink toolboxes (Kleiner, Brainard, & Pelli, 2007) running in Matlab (MATLAB, 2017). Participants viewed the display screen (19-inch monitor, 1024 x 768 pixels resolution, 85-Hz refresh rate) from a distance of approximately 57 cm and their viewing position was stabilized by means of a forehead-and-chin rest. Eye movements were recorded (at a sampling rate of 1000 Hz) from the right eye using an Eyelink CL eye-tracker system (SR-Research Ltd., ON, Canada). At the beginning of each block, a 5-dot calibration routine was performed. Eye-movement monitoring was intended to ensure that participants' gaze remained fixated at the screen center. A given trial was discarded if participants moved their gaze more than 2° away from the central fixation cross, which happened in 1.9% of all trials.

2.3. Stimuli

All six stimulus configurations consisted of two white circles (luminance: 1.83 cd/m2) with a radius of 1° of visual angle, which were presented on a black background (luminance: 0.01 cd/m2). Each two-circle configuration was arranged vertically, subtending 1° x 2.6° of visual angle. In each circle, a square-shaped indent (0.4° x 0.4°) was removed from the top or the bottom, thus forming a “pacman” inducer element. The grouped target (Figure 2A) was an arrangement with both indents facing towards the ‘inside’ (i.e., the horizontal midline of the screen), which generated a vivid impression of a symmetrically organized, illusory Kanizsa rectangle. For the ungrouped target (Figure 2B), both indents were arranged to face ‘outwards’ (i.e., away from the midline), which also resulted in a symmetrical configuration, but without the emergence of an illusory object. Finally, distractor configurations (Figure 2C) consisted of a pair of circles with both indents removed from either the top or the bottom, so that no illusory figure could be formed. Stimuli were presented at six lateral positions, three to left and three to the right of the central white fixation cross at eccentricities of 5º, 10º, and 15º, respectively (fixation cross: size 0.4º x 0.4º). Within a given trial display, either a grouped or an ungrouped target would be presented with equal probability at one of the six possible locations; the remaining five locations were occupied by a distractor configuration, with an upward or downward orientation of both inducers (orientation randomly selected for each distractor position). Prior to the search display, a premask display presented complete white circles at the same locations as the subsequent pacman inducer elements (see Figure 2D for an example trial sequence).

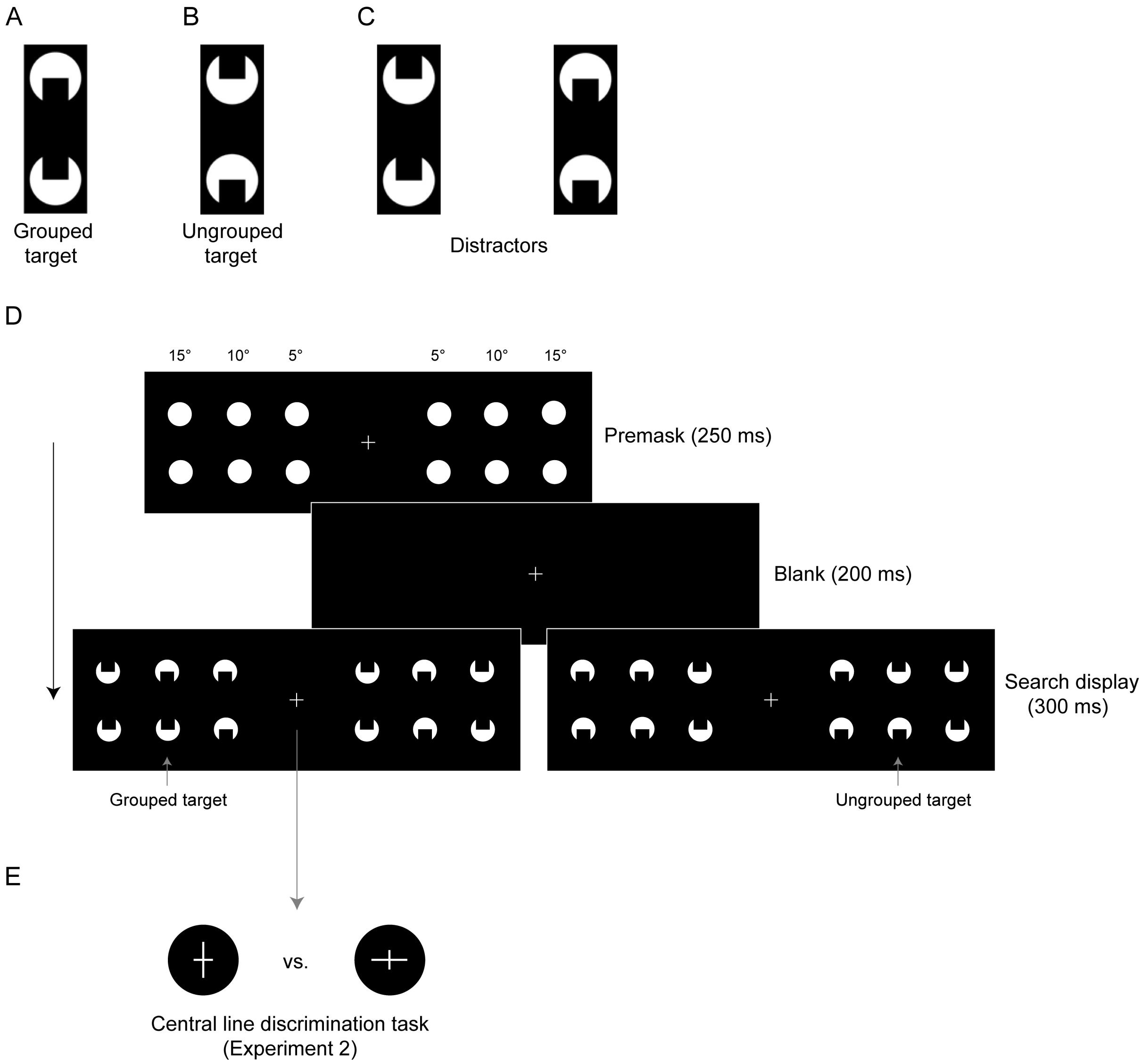

Figure 1. Illustrations of the grouped (A) and ungrouped (B) targets and the distractor configurations (C), as presented in the experiments. Panel (D) depicts an example trial sequence in Experiment 1. A premask display presented six filled placeholder circles for 250 ms, which was followed by a blank screen for 200 ms. Next, the search display appeared and remained on the screen for 300 ms, either presenting a grouped (left) or an ungrouped (right) target (in the example depicted, both targets are presented at an eccentricity of 10º). (D) In Experiment 2, the trial sequence was the same, except that an additional, foveal task was added to the search display, which required a line length discrimination of the (vertically or horizontally stretched) fixation cross.

2.4. Procedure

The experiment was conducted in a dark, soundproof experimental room. Participants were instructed to fixate the cross in the screen center for the entire trial duration and localize the target in the left/right half of the display (which was assumed to require changes of the attentional breadth for stimuli at the peripheral locations) – responding to any target detected at any of the three positions in the left/right visual field with the left/right arrow key on the keyboard. Participants were asked to respond as accurately as possible, without any time restriction.

The experiment consisted of four blocks in total with short breaks in-between. Each block presented 120 trials. Two consecutive blocks presented a grouped target and the other two blocks an ungrouped target. The order of presentation of the grouped/ungrouped target blocks was counterbalanced across participants. Grouped and ungrouped targets were presented in a blocked fashion to ensure that observers could prepare specifically for a given target stimulus. The position of the target (at the various eccentricities in the left or right display half) was randomized across trials so that participants could not direct attention to the target location beforehand, thus requiring a rather broad attentional focus at the beginning of each trial. Each block presented 20 trials for each position and display half, yielding 480 trials in total.

Each trial started with the presentation of the fixation cross for 250 ms. Next, the premask was presented for 250 ms, followed by a blank screen shown for 200 ms. Subsequently, the search display was presented for 300 ms. After the offset of the search display, a 'blank' screen with only the fixation cross remained in view for 1750 ms, providing sufficient time for the pupil dilation to be measured (e.g., Brocher et al., 2018). Following the dilation period, participants were asked to provide their response by pressing the left/right arrow key. An example trial sequence is depicted in Figure 1D. The experiment lasted approximately one hour in total, including the instruction of the participants, a short practice session (10 trials per target type), and the eye-tracker calibration routine at the beginning of each block.

2.5. Pupillometry

The raw eye-tracking data from all participants was exported into a text-format sample report using the EyeLink DataViewer (EyeLink Data Viewer, 2007). For all preprocessing steps as well as the statistical analysis of the pupil-size (and response-accuracy) data, we used R Studio (RStudio Team, 2015). Trials with incorrect behavioral responses were discarded from the data proper. We also excluded trials with blinks, trials on which the pupil-size measure was larger than three standard deviations from the overall mean, trials which yielded fewer than 60% of useable data points, and trials in which overt eye-movements were made (see Brocher et al., 2018; Mathôt, Fabius, Van Heusden, & Van der Stigchel, 2018). In total, 4.6% of all trials were excluded by this elimination procedure (6.1% in Experiment 2). Note that the eye tracker failed to record data for one participant (Experiment 1), and, hence, the pupillometry analyses presented below are based on a sample of 29 observers.

Pupil size was calculated by means of a subtractive baseline correction (see Brocher et al., 2018; Mathôt et al., 2018, for a similar procedure). Thus, for each trial and participant, we extracted the maximum pupil size during the 250-ms interval when the premask display was presented (baseline), and then subtracted this baseline measure from the maximum pupil size after the presentation of the stimulus display during the 1750 ms dilation period (i.e., after search-display offset).

3. Results

3.1. Response accuracy

Trials on which participants did not maintain central fixation were excluded from the analysis (1.9% of all trials). Overall, the mean percentage of correct responses was 70.5%. Figure 2 presents the mean accuracies as a function of eccentricity, separately for the two types of target configuration. Individual mean accuracies were analyzed using a repeated-measures analysis of variance (ANOVA) with the factors Target Configuration (ungrouped, grouped) and Eccentricity (5º, 10º, 15º). Greenhouse–Geisser corrected values are reported in case Mauchley's test of sphericity was significant ($p < .05$). This analysis revealed a main effect of Target Configuration, $F(1, 29) = 62.27$, $p < .001$, with higher response accuracy for grouped (79.2%) versus ungrouped targets (62.2%). There was also a significant main effect of Eccentricity, $F(2, 58) = 48.84$, $p < .001$: overall, accuracy decreased with increasing distance of the target from fixation (78.2%, 73.8%, 59.9% for eccentricities of 5°, 10°, and 15°, respectively). Importantly, there was also a significant Target Configuration x Eccentricity interaction, $F(1.54, 44.66) = 24.62$, $p < .001$. Holm *post-hoc* tests revealed that for the grouped target, there were significant differences between the 5° (91.1%) and both the 10° (84.4%, $p = .036$) and 15° (61.7%) eccentricities, as well as between the 10° and 15° eccentricities (p's $< .001$). Thus, in the grouped-target condition, accuracy dropped significantly the further away from fixation the target appeared. By contrast, in the ungrouped-target condition, there were no significant differences across the three eccentricities (all *p's* > .05), with the mean response accuracy (62%) being overall comparable to performance in the grouped target condition at the most distant, 15°-eccentricity position, *p* = .791. Together, this pattern shows that an increase in target eccentricity substantially reduced localization accuracy for the grouped target, while the localization of the ungrouped target was less accurate overall (i.e., even at the position closest to fixation) and not modulated further by target eccentricity.

Of note, performance in all conditions was significantly above the 50% chance level, $t(29)$'s > 3.58, p's < .001. However, in order to further exclude the possibility that the significant interaction was due to the ungrouped targets revealing a floor effect (i.e. with their respective performance levels being somewhat, i.e. some 10%, above chance), we additionally arcsine-transformed the accuracy data to improve normality. The pattern of results for these arcsine-transformed accuracies stayed the same as described above, revealing significant main effects of Target Configuration, $F(1, 29) = 72.80$, $p < .001$, and Eccentricity, $F(2, 58) = 50.17$, $p < .001$, and again a significant Target Configuration x Eccentricity interaction, $F(2, 58) = 36.40$, $p < .001$. Holm *post-hoc* tests also again showed the same pattern as described above. The significant interaction is therefore unlikely to be due to a floor effect in the ungrouped targets.

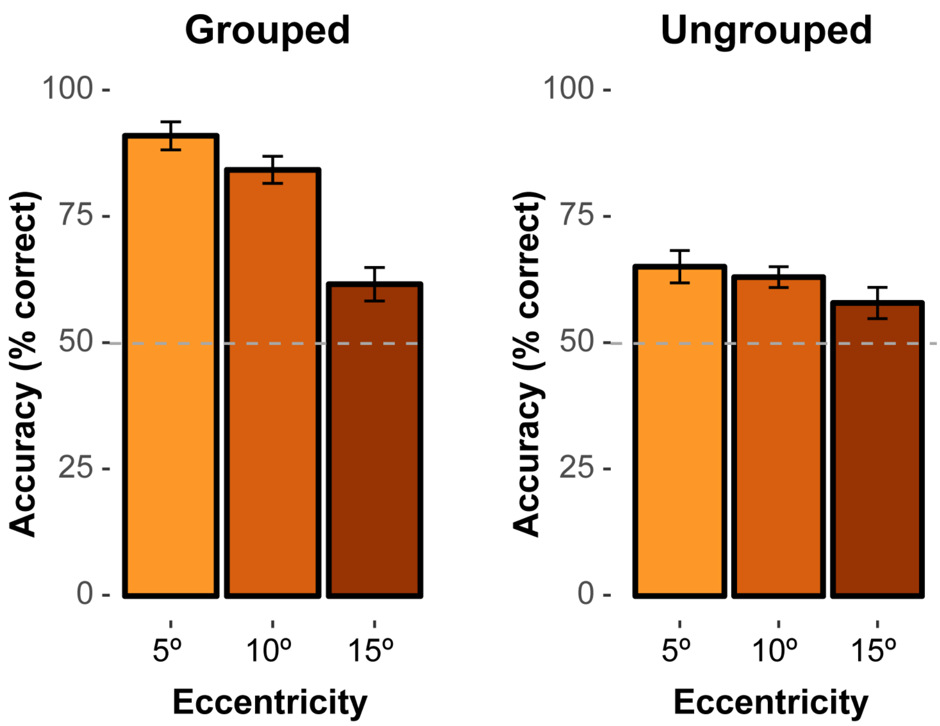

Figure 2. Mean accuracies (% correct), with within-subject 95% confidence intervals, for grouped (left) and ungrouped (right) targets as a function of target eccentricity.

3.2. Pupillometry

Figure 3A depicts the time courses of the pupil size deviations (relative to the baseline) for each target eccentricity, separately for the grouped (left) and ungrouped (right) target configurations (in arbitrary units). As mentioned above, only trials with correct behavioral responses were included in the pupil size analyses, in order to ensure that potential variations in the pupil size reflect actual target processing (and are not simply related to some error-related processes, see for example Maier, Ernst, & Steinhauser, 2019). Note that due to the subtraction procedure (see Methods section Pupillometry), all mean pupil deviations took on a negative value, with more negative values denoting smaller pupil sizes (and, accordingly, a narrower focus of attention).

To start with, it is instructive to take a look at the overall curves depicted in Figure 3A: following the appearance of the fixation cross, the pupil at first slightly constricts relative to the baseline level before dilating in response to the black background. Next, upon the (250-ms) presentation of the premask display, the pupil constricts again due to the sudden onset of the six bright (i.e., white) placeholders. Note that we included the premask display to allow for a global orientation process as to where potential target (and distractor) items will subsequently appear. The pupil keeps constricting during the (200-ms) intervening blank period and over the (300-ms) exposure of the search array, responding to the bright target and distractor stimuli. And then, after the offset of the search array, the pupil dilates over the 1750-ms 'dilation' period during which only the fixation cross remains in view on a black screen background. Thus, the pupil response is strongly light driven during the first part of the trial, swamping the expression of any subtle covert attentional orienting processes. Such processes become only observable in differences of the pupil size during the dilation period, with the fading of light response. This is not to say that the covert attentional processes that may be tracked by changes in pupil size commence only in the dilation period; rather, these processes are set in motion already during the presentation of the search array, but they would be 'unmasked' only by the fading of the light response. Figure 3B presents the corresponding mean pupil-size deviations observed during the dilation period, for each condition.

Individual mean pupil-size deviations from baseline were again analyzed by means of a repeated-measures ANOVA with the factors Target Configuration and Eccentricity. While there was no main effect of Target Configuration, $F(1, 28) = 0.92$, $p = .347$, the main effect of Eccentricity was significant, $F(1.66, 46.48) = 4.54$, $p = .021$, with pupil size being overall smaller (indicative of a narrower focus of attention) when targets were presented closer to fixation (-202.58, -187.17, and -186.87 for eccentricities of 5º, 10º, and 15º, respectively).

Importantly, the Target Configuration x Eccentricity interaction was also significant, $F(2, 56) = 3.65$, $p = .032$. Holm *post-hoc* tests showed that for the grouped-target condition, there was a significant difference of the 5° eccentricity (M = -217.14) relative to both the 10° (M = -184.09), $p < .001$, and the 15° eccentricity (M = -191.05), $p < .019$. Thus, for grouped targets, the pupil size was significantly smaller when the target appeared close to fixation. For the ungrouped-target condition, eccentricity variations did not influence the size of the pupil, and the pupil diameter was overall comparable to the most distant, 15° eccentricity position in the grouped-target condition, p's > .05. Thus, the pupillometry data revealed a comparable pattern to the response accuracies, with a smaller pupil size (indicative of a narrower attentional focus) for grouped targets presented closer to fixation. For the ungrouped targets, the pupils were more dilated irrespective of target eccentricity (indicative of a rather broad focus of attention).

To further assess the specific dynamics of the pupillary response to grouped targets, we performed an additional analysis of the pupillometry data by subdividing the total (1750-ms) dilation period into two halves: an early and a late dilation period (of 875 ms each). Separate analyses of both halves showed that the above-described constriction of the pupil for the grouped target at the near-fixation location emerged only late in (i.e., in the second half of) the dilation period (*p's* < .05 for the comparison of the 5° eccentricity with the 10° and 15° eccentricities), while not yet manifesting during the early period (all *p's* > .05 across all three eccentricities) – consistent with the 'unmasking' notion outlined above. This pattern may thus be taken to indicate that attention was initially distributed rather broadly (to orient in the entire search array) before focusing upon the grouped target (at least when presented at a central location) - thereby improving the resolution of attention for target-related processing.

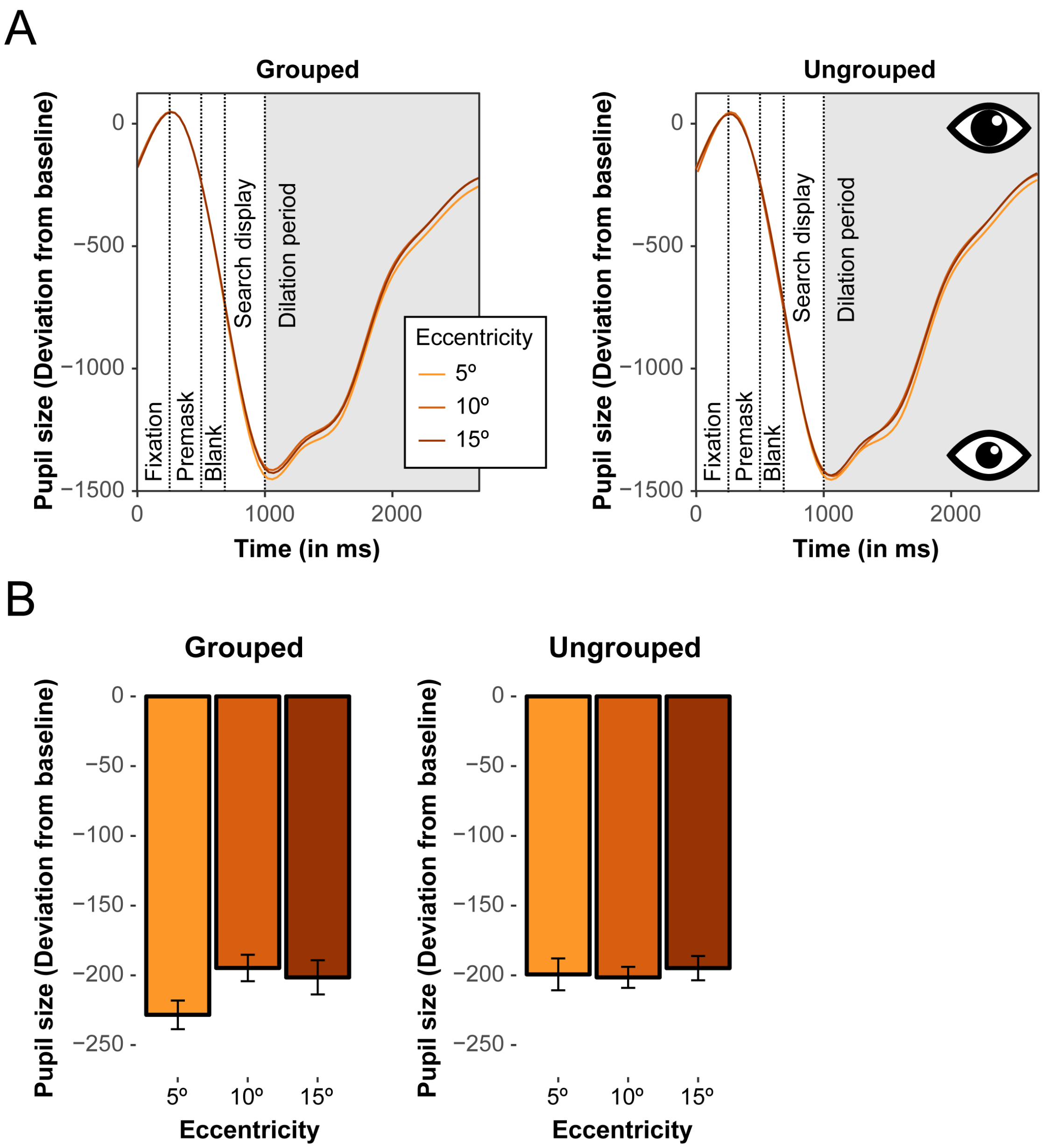

Figure 3. (A) Time courses of the pupil-size deviation from baseline, in arbitrary units, for varying target eccentricities (of 5°, 10°, and 15°), separately for grouped (left) and ungrouped (right) target configurations. The dashed vertical lines denote the sequence of display frames on a given trial (fixation, premask, blank, search display, and dilation period, respectively). (B) Mean pupil size deviations from baseline (with corresponding within-subject 95% confidence intervals) for grouped (left) and ungrouped (right) targets as a function of target eccentricity, as measured in the dilation period (the gray shaded area in the figures in panel A). Note that the subtraction procedure used to calculate mean pupil-size deviations yielded negative values, where a larger negative deviation corresponds to a smaller pupil size (thus, reflecting a comparably narrow attentional focus).

4. Discussion

Employing a visual search task, Experiment 1 examined for variations of the attentional breadth as associated with the localization of more versus less grouped target configurations at varying eccentricities. The results revealed a grouping benefit which scaled with eccentricity: grouped targets appearing closer to fixation were detected with higher accuracy than more distant targets. No comparable benefit was found for ungrouped targets, which exhibited a level of performance overall comparable to the grouped target at the greatest eccentricity. The pupillometric data essentially mirrored this pattern; in particular, pupil sizes were smaller for grouped targets appearing closer to fixation, as compared to more dilated pupils for more distant grouped targets and for all ungrouped targets (irrespective of their eccentricity). Moreover, this constriction of the pupil for grouped targets close to fixation appeared to occur relatively late in time, in the second half of the dilation period. Together, this pattern of results shows that the observable grouping benefit covaries with the availability of attentional resources: Grouped targets at central locations elicit (after some time) a relatively narrow focus of attention and are detected with high accuracy, whereas more distant grouped targets (and ungrouped targets at all locations) require attention to be distributed more broadly across the entire trial while still being detected only with relatively low (though, with above-chance level) accuracy. Attention (as measured in the pupillometric data) thus appears to scale with the concurrent grouping demands. The attentional focus seems to be initially set broadly by default, covering a large area of the visual field, yet only at a relatively low resolution. After a broad scan of the array, the grouped target triggers a narrowing of the focus, increasing the attentional resolution (and, correspondingly, performance; see Shepherd & Müller, 1989). In this view, grouping benefits performance in particular when a sufficient amount of attentional resources is available at the locations of the to-be-grouped items (see, Nowack et al., 2021).

Of note, this result pattern would appear to be inconsistent with an alternative theoretical view, which assumes that attention is allocated upon the completion of preattentive-automatic grouping operations (e.g., Mattingley et al., 1997). That is, the preattentive integration of separate parts into a grouped object would enhance the saliency of that object (e.g., Kimchi, Yeshurun, Spehar, & Pirkner, 2016; Rauschenberger & Yantis, 2001), as a result of which attentional resources would be attracted more strongly by the grouped, salient configuration. Such a process of essentially object-based attentional capture would be expected to be associated with focused attention being allocated towards the grouped, salient object early on during processing. However, in our experiment, attention was initially set broadly across the entire search array and focused only after some considerable delay. This pattern appears less consistent with the notion of an automatic (i.e., purely preattentive) attraction of attention by salient object groupings.

Experiment 2 was designed to further test the strength of the linkage between grouping and the availability of attention, that is, whether effective grouping depends on the amount of attentional resources available at the target location. As described above, grouped targets at near-foveal locations were detected very accurately with a narrow focus of attention, while performance dropped for more peripheral, grouped targets for which attention was more broadly distributed. This pattern might be taken to indicate that a certain amount of attentional resources has to be available in order to trigger effective object completion. This idea was further tested in Experiment 2 by combining peripheral search for a grouped/ungrouped target configuration with an attentionally demanding foveal task (see, e.g., Mack, Tang, Tuma, & Kahn, 1992, and Moore & Egeth, 1997, for a similar logic). The addition of such a second task allowed us to assess peripheral search performance when attentional resources were partly unavailable (due to being occupied in the center) – thereby impacting the allocation of attention to the lateral target grouping.

Experiment 2

Experiment 2 was in most respects comparable to Experiment 1 – except that a dual-task paradigm was implemented in order to reduce the amount of attentional resources available to process the peripheral target configurations. A given trial would again consist of an initial premask, followed (after some delay) by a search display (similar to Experiment 1). In addition, Experiment 2 consisted of two experimental parts, which were presented in counterbalanced order across participants: In the "*single-task*" part of the experiment, observers were required to discern the presence versus absence of a (grouped or ungrouped) lateral target among distractors. We deliberately introduced a (target present vs. absent) detection task in Experiment 2 (as compared to the left/right target-localization task used in Experiment 1) in order to rule out a potential strategy of restricting the search to only one half of the display. In more detail, in the localization task (as used in Experiment 1), monitoring the stimuli in only one display half would potentially allow observers to infer the left/right location of the target in the whole display, that is: if it can be ruled out that the target is not present on the searched side, it would have to be located on the opposite side (allowing a default "opposite-side" response). Such a possible strategy was avoided by introducing a target-detection task (in Experiment 2): the introduction of target-absent trials requires observers to search both display halves in order to accurately determine the presence (vs. the absence) of a target.

In the "*dual-task*" part of the experiment, the same peripheral target-detection task was used but it was additionally accompanied by a second, attentionally demanding foveal line-length discrimination task. To elaborate, together with the onset of the search display, the central fixation cross was presented with the crossing line segments stretched either vertically or horizontally, and observers were asked to report the orientation of this stretched cross (see Figure 1E and Mack et al., 1992, for a comparable procedure). If detection of the grouped target would still reveal a benefit (relative to the ungrouped target), despite a substantial amount of attentional resources being occupied by the foveal task, this could be taken to indicate that (Kanizsa-type) grouping of the target fragments occurs even when only limited attentional resources are available to trigger object completion.

2. Materials and Methods

2.1. Participants

Experiment 2 was by a large extent comparable to Experiment 1, apart from the following changes: The experiment was separated into two distinct parts. In the single-task part of the experiment, the sequence of events on a given trial was essentially comparable to Experiment 1 (see Figure 1D), except that observers were now asked to report the presence versus absence of the target (rather than to left/right localize the target, as in Experiment 1). Observers were instructed to respond as accurately as possible, without time restrictions, by pressing the left [right] arrow key on the keyboard to target presence [absence], respectively. As mentioned above, the change from a localization to a detection task was implemented in order to prevent observers from simply using a strategy that bases the response on the monitoring of only one half of the display. In target-absent displays (one third of all trials), six randomly oriented distractors would be presented. In target-present displays, the target would be located at the intermediate (10°-eccentricity) location in either the left or the right display half (with equal probability). Only one target eccentricity was used to ensure a sufficient amount of trials per condition, while maintaining an appropriate length of the experiment and to control for potential influences from crowding effects at variable target eccentricities. Recall that in Experiment 1, the middle 10°-eccentricity location also exhibited a robust grouping benefit, justifying the use of this target eccentricity in Experiment 2. The remaining five other locations in target-present displays (and all six locations in target-absent displays) were again occupied by a distractor configuration (with randomly selected upward or downward orientation of the indents).

In the dual-task part of the experiment, the lateral search task was identical to the procedure in the single task. Critically, however, in an additional foveal task, the initially presented fixation cross (0.4° × 0.4°) changed the length of its arms during the presentation of the search display, revealing either a horizontally stretched cross, 0.5° × 0.3°, or a vertically stretched cross, 0.3° × 0.5° (see Figure 1E). It should be noted that changing the cross dimension from 0.4° × 0.4° (in the single-task part) to either 0.5°× 0.3° or 0.3°× 0.5° (in the dual-task part) did not introduce an overall luminance change in the display center since the overall physical stimulation remained constant. Participants were asked to indicate whether the horizontal or the vertical line of the fixation cross was longer by pressing the left or right arrow keys, respectively. The response to this foveal task was issued by a response cue, which was presented on the screen *after* observers responded to the presence/absence of a lateral search target – thus, providing observers with an identical trial sequence in the lateral search task both in the single- and dual-task conditions. Observers were instructed to prioritize this new, foveal judgment task over the lateral search task.

A new sample of 30 participants (11 males; mean age 26.77 [SD = 6.83] years) with normal or corrected-to-normal vision took part in Experiment 2, either for course credits or payment (9 €). The sample size was again determined on the basis of the above described power analysis. For the eye-movement recordings, the sampling frequency was reduced to 250 Hz (see Brocher et al., 2018) to prevent high levels of noise during data acquisition. Central eye gaze was once again monitored, and a given trial was discarded when a saccade (indicative of an overt orienting response) was made (2.6% of all trials).

The order of the single- and dual-task parts of the experiment was counterbalanced across participants where each part consisted of four blocks, with short breaks in-between. Each block presented 60 trials in randomized order: 20 target-present/grouped, 20 target-present/ungrouped, and 20 target-absent trials. On target-present trials, the target was equally likely to appear in the left or right display half. In the dual-task part of the experiment, the horizontally or vertically oriented fixation cross appeared with equal probability. Experiment 2 consisted of 480 trials overall, with two experimental factors: target configuration (grouped, ungrouped, absent) and task load (single, dual task). The total experiment lasted approximately one hour, including the instruction of the participants, a short practice session (of 18 trials) at the beginning of each experimental part, and the eye-tracker calibration routine at the beginning of each block.

Preprocessing of the pupillometry data, followed the same routines as in Experiment 1, which led to the exclusion of 6.1% of all trials.

3. Results

3.1. Response accuracy

To ensure that attention was engaged in the foveal line-discrimination task, we only analyzed trials in which the orientation of the central fixation cross was correctly identified (92.4% of all trials). Moreover, target-absent trials (which yielded overall 78.1% correct responses, with more accurate responses under the single- as compared to the dual-task load, 84.8% vs. 71.4%, respectively, $t(29) = -4.95$, $p < .001$) were also excluded from the data proper before the analysis of the lateral target detection accuracies.

Figure 4A presents the mean accuracies in the peripheral search task for the two types of target configuration as a function of task load. Individual mean accuracies were analyzed using a repeated-measures ANOVA with the factors Target Configuration (ungrouped, grouped) and Task Load (single task, dual task). This analysis revealed a main effect of Target Configuration, $F(1, 29) = 40.32$, $p < .001$, with overall higher response accuracies (by 23.4%) for grouped than for ungrouped targets (which is essentially comparable to performance for the middle 10º position in Experiment 1, where the grouped target revealed a comparable benefit of 21.2% relative to the ungrouped target, $t(29) = 0.62$, $p > .05$). The main effect of Task Load was also significant, $F(1, 29) = 7.87$, $p = .008$: responses were more accurate overall under single- (63.9%) than under dual-task (55.5%) conditions; that is, having to perform the foveal task indeed resulted in a substantial reduction of performance on the peripheral search task. The target configuration by task load interaction was not significant, $F(1, 29) = 0.30$, $p = .586$. Thus, the grouped target substantially improved performance (relative to the ungrouped target) both when attention was fully available (in the single-task condition) and when a rather large amount of attention was absorbed by the secondary, foveal task (in the-dual-task condition).

As in Experiment 1, we again arcsine-transformed the accuracy data to improve normality and to exclude the possibility that the nonsignificant interaction in the ANOVA was caused by a floor effect. This analysis revealed significant main effects of Target Configuration, F(1,

29) = 42.07, $p < .001$, and Task Load, $F(1, 29) = 7.58$, $p = .010$ but again no significant interaction ($p > .05$), thus mirroring the above-described results.

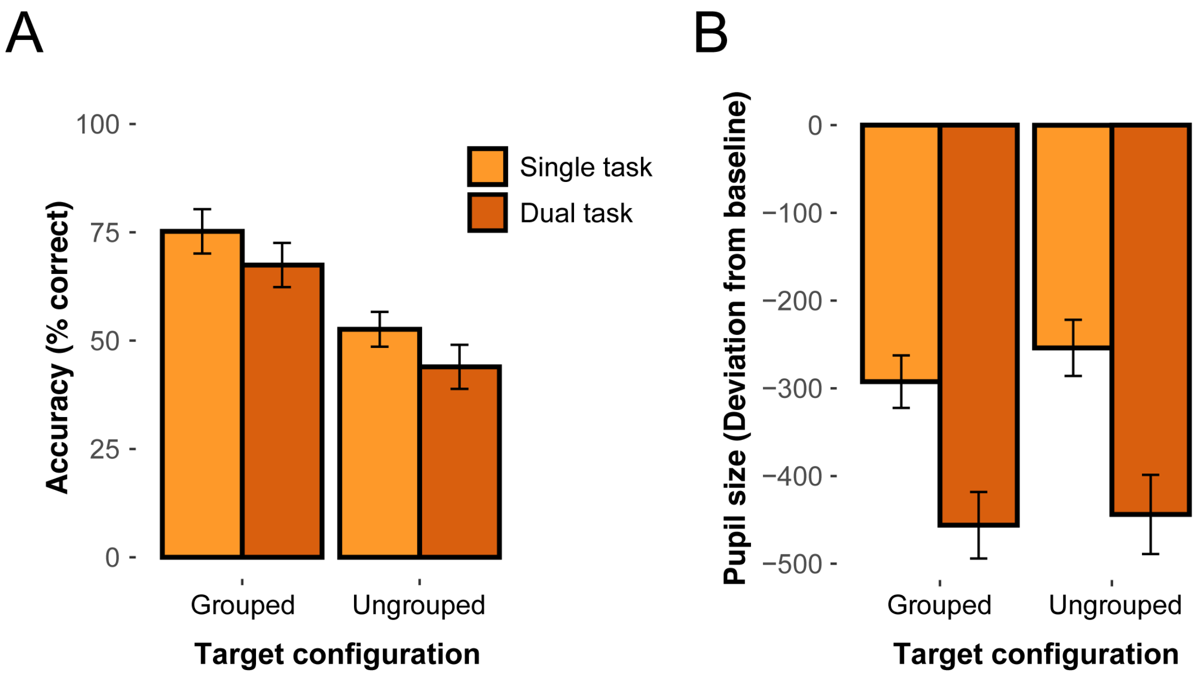

Figure 4. Results in the peripheral search task in Experiment 2 (given correct performance in the foveal task under dual-task conditions). (A) Mean accuracies (% correct) and (B) mean pupil size (with corresponding 95% within-subject confidence intervals) for grouped and ungrouped targets as a function of task. Pupil size measures depict the deviations from baseline as measured in the dilation period. Note that the use of a subtraction procedure to calculate mean pupil deviations resulted in negative values, with a larger negative deviation corresponding to a smaller pupil size (thus reflecting a comparably narrow focus of attention).

3.2. Pupillometry

Figure 4B presents the mean pupil-size deviations from baseline, for each experimental condition during the dilation period (analogous to the procedure described in Experiment 1). Recall that due to the subtraction procedure, all mean pupil deviations revealed negative values, where more negative values indicate that the pupil size became smaller, indicative of a narrower focus of attention. Trials with incorrect behavioral responses (in both the central discrimination and the peripheral detection task) were again discarded from the data proper (to ensure that pupil size variations reflect processing of the target and are not contaminated by error-related variations). Individual mean pupil-size deviations were analyzed by a repeated-measures ANOVA with the factors Target Configuration and Task Load.[2] The results revealed a main effect of target configuration, $F(1, 29) = 9.42$, $p = .004$, with smaller pupil sizes for grouped ($M = -374.26$) versus ungrouped targets ($M = -348.84$). There was also a significant main effect of task load, $F(1, 29) = 31.75$, $p < .001$, with pupil size being markedly smaller when participants had to focus on a second, foveal task ($M = -449.95$), as compared to the single-task condition (M = -273.15). Importantly, however, the Target configuration × Task Load interaction was not significant, $F(1, 29) = 1.42$, $p = .243$. Overall, the pupillometry data thus revealed a comparable pattern of results as for the response accuracies, showing a clear effect of task load: Attention was focused more strongly at central locations when the additional foveal task had to be performed (evidencing the resource-demanding nature of the central task). However, there was also a grouping benefit: attention was more focused when a grouped target was presented than when the target was ungrouped. This grouping benefit in the pupillometry data was essentially independent of the task load.

4. Discussion

In Experiment 2, a secondary, foveal task was introduced to investigate how the availability of attentional resources would impact processing of the lateral search items. The results showed that the foveal task was indeed successful in binding attentional resources, rendering search for the lateral targets less accurate. Nevertheless, detection of the grouped target exhibited a reliable performance benefit relative to the ungrouped target and this grouping benefit was independent of whether or not a foveal task had to be completed.

Concurrent measures of pupil size again were comparable to behavioral performance, with more dilated pupils for the single- as compared to the dual-task condition. This indicates that the amount of available resources and their potential allocation to the peripheral search items was directly reflected in the changes of the pupil diameter – with an overall stronger central attentional focus under dual-task conditions. Moreover, there was an effect of grouping on the pupillometric data: pupils were more dilated for ungrouped than for grouped targets (comparable to Experiment 1), independently of the task load. This indicates that search for ungrouped targets is associated with a broader distribution of attentional resources (that comes along with a lower attentional resolution) than search for grouped targets, likely

[2] Note, that target-absent trials were also excluded from the data proper before the main analysis of the pupil sizes in target present trials. However, an additional analysis of target-absent trials also revealed a significant difference in pupil size between single ($M = -295.13$) and dual task ($M = -433.39$) conditions, $t(29) = 5.69$, $p < .001$.

because grouped targets summon the available attentional resources more efficiently than the corresponding ungrouped targets. Importantly, this benefit for the grouped target was already evident when only a limited amount of attentional resources was available to trigger object completion.

While a benefit of grouping appeared to occur independently of whether attention was partly focused in the display center or not, the overall performance accuracy in the single task condition of Experiment 2 (63.9%) was somewhat lower than performance for the same 10°-eccentricity target position in Experiment 1, which yielded a mean accuracy of 73.8%, $t(29) = 5.39$, $p < .001$. This enhanced performance in Experiment 1 may be due to the somewhat easier localization task, and the blocked presentation of the target configurations, which presumably helped observers prepare for an upcoming trial. However, even though there were some minor differences in task difficulty, it should be noted that the overall grouping benefit (of around 20%) was comparable across both experiments.

5. General Discussion

The current study investigated whether perceptual grouping could facilitate visual search and whether such a grouping benefit would vary with the amount of available attentional resources. Our experiments were in part motivated by recent findings from experiments with neuropsychological patients who showed deficits of selective attention due to parietal brain damage, which revealed that object grouping was ineffective in parts of the visual field where attention was lacking (Nowack et al., 2021; see also Gögler et al., 2016; Conci et al., 2018) – the theoretical implication being that effective perceptual grouping depends on the availability of attentional resources. To validate these previous findings and extend them to healthy observers, the current study tracked the engagement of covert attention by measuring pupil dilations while systematically comparing visual search for grouped versus ungrouped targets with targets appearing either at varying eccentricities relative to central eye-fixation (Experiment 1), or during a concurrent, attention-demanding central (foveal) discrimination task (Experiment 2).

Experiment 1 used a visual search task that required participants to localize a grouped or, respectively, ungrouped Kanizsa-type target among distractor configurations in peripheral vision. The behavioral results revealed grouping to facilitate target localization: response accuracies were higher for grouped (79.2%) than for ungrouped target configurations (62.2%). This essentially replicates previous findings showing that grouping by collinearity and closure may lead to an increase of the conspicuity of the Kanizsa target figure, thereby facilitating search (Conci et al., 2007; Conci et al., 2011; Kimchi et al., 2016; Nie et al., 2016; Wiegand et al., 2015; Pomerantz & Portillo, 2011). Moreover, the performance benefit for grouped targets was dependent on the eccentricity at which the target was presented: at an eccentricity of 5°, grouped targets were localized with very high accuracy (91%), but accuracy dropped monotonically with increasing distance from fixation (to 84% and 62% at eccentricities of 10° and of 15°, respectively). It is typically assumed that the availability of attention is highest in central vision and decreases with increasing distance from the fovea (Ducrot & Grainger, 2007; Jacobs, 1979). Moreover, when attention is distributed over a larger area of the visual field, its resolution decreases, as compared to when attention is more narrowly focused (Eriksen & Yeh, 1985). The eccentricity effect in the current experiment may thus indicate that the efficiency of grouping scales with the gradient of attentional resolution. By contrast, performance for the ungrouped targets was relatively low throughout (e.g., only 65.2% at the most central, 5°-position) – indicating that an object which is not grouped is also not processed more efficiently when more attentional resources are available (i.e., closer to fixation). Together, this pattern of results lends support to the idea that successful grouping is linked to the availability of attentional resources, which are particularly concentrated in more central vision and which scale with changes of the attentional breadth.

This conclusion is also supported by our pupil-size data. Previous studies showed that the pupillary light reflex reveals a constriction of the pupil in response to brightness and a concurrent dilation in response to darkness (Mathôt, 2018). Moreover, it was reported that covertly attending to a bright or dark stimulus elicits a comparable pupillary light reflex as if one would be looking directly at a given stimulus, albeit with a much weaker modulation (Binda & Murray, 2015; Binda, Pereverzeva, & Murray, 2013, 2014; Mathôt, Dalmaijer, Grainger, & Van der Stigchel, 2014; Mathôt, van der Linden, Grainger, & Vitu, 2013). Covert changes of the attentional breadth were also evident in the current study, as participants had to attend to bright stimuli in the periphery without making any eye movements (however, these changes in allocating attention occurred in the absence of luminance manipulations, since all stimuli always had the same amount of light entering the eyes, i.e., there was no bright vs. dark stimulus manipulation). In the dilation period, after the presentation of the stimuli, we observed systematic differences in pupil size, depending on the type of target and eccentricity. For instance, with grouped targets, the pupil was dilated initially, while it constricted towards the end of the dilation period for the proximal target at 5°, suggesting that attention is initially distributed broadly in order to attend to and process the more distant stimuli, while the central, grouped target is then focused later on. For correctly localized targets in the ungrouped target condition, however, the pupil diameter was overall constant and comparable to the most peripheral, 15° position in the grouped target condition. Overall, these results (in particular with grouped targets) accord with the findings of Brocher et al. (2018) who reported that the size of the pupil varies in relation to stimulus-to-fixation distance when participants covertly shift attention to peripherally presented stimuli. Similarly, it has also been shown that the pupil is also more dilated when attention spreads more broadly as compared to when a more narrow focus of attention is required (Daniels et al., 2012; Ivanov et al., 2019; see Mathôt, 2020, for a review).

Together, the pupil-size effects in Experiment 1 thus show that the attentional focus scales with the benefit of grouping in the target: attention appears to be initially distributed broadly by default, covering a large area of the field, though only at a relatively low resolution. After a broad scan of the array, the grouped target triggers a narrowing of the focus (evident especially with a target at 5º eccentricity), increasing the attentional resolution. By contrast, ungrouped targets are processed inefficiently at all eccentricities.

Alternatively, one could argue that the efficiency of grouping scales with visual acuity. In central (foveal) vision, the concentration of cones is very high and then decreases at eccentricities beyond 10º of visual angle (Pouget, 2019). Thus, high visual acuity is only available in foveal and peri-foveal vision, which however already encompassed the two inner-most target locations in our search displays. From a visual-acuity perspective, stimuli at larger eccentricities should elicit poorer performance than more proximal ones independently of their configuration. In Experiment 1, however, we found no significant difference in performance for ungrouped target configurations across all three eccentricities (there was an eccentricity-dependent effect only for the grouped targets), which renders it unlikely that the results are due to an overall gradient of visual acuity. Moreover, Brocher et al. (2018) also assessed whether the cortical magnification factor and associated variations of visual acuity (across a rather large range of eccentricities of up to 42.5º) may lead to variations in pupil size (independently of concurrent attention shifts). Their results, however, indicated that differences in eccentricity and related changes of the density of photoreceptors in the retina cannot explain the observed change in performance; instead, the observed variations in accuracy as a function of eccentricity can be related primarily to concurrent attention shifts.

In Experiment 2, the availability of attentional resources in the periphery was further restricted by means of an attention-demanding foveal discrimination task. The question was whether the grouping benefit in the peripheral search task would still be evident when a substantial amount of attentional resources is bound elsewhere. The behavioral results again showed that grouping facilitates target detection: response accuracies were by 23.4% higher for grouped than for ungrouped target configurations. Moreover, performance was affected by the attention-binding foveal task: response accuracies were reduced, by 8.4%, under the dual- relative to the single-task load. Importantly, however, the grouping benefit manifested (and its magnitude was independent of) whether or not observers had to perform the attention-binding foveal task. This shows that grouping in the peripheral target can still give rise to a benefit even when only rather limited attentional resources are available. The pupil-size data again mirrored the behavioral results: the pupil size was overall smaller when participants performed the search under dual-task conditions, as compared to the single task where more attentional resources were available to process the targets in the periphery. This finding is overall consistent with findings showing that a high attentional load at the fovea goes along with a comparably narrow attentional focus (Daniels et al., 2012; Kornrumpf & Sommer, 2015). Moreover, as in Experiment 1, detection of grouped targets was associated with smaller pupil sizes compared to ungrouped targets, again indicating that grouped targets are not only easier to detect but also summon attention more efficiently than ungrouped target stimuli. The results from Experiment 2 thus show that a grouping can facilitate performance and modulate covert attention spreading even when only residual attentional resources are available.

Previous studies that employed a foveal task to bind attentional resources have revealed that observers are unable to identify a grouping pattern in the periphery when they were not attending to these groupings (Mack et al., 1992; but see Moore & Egeth, 1997). This may be taken to suggest that object-based selection operates only within spatially attended regions (Lavie & Driver, 1996). However, extended practice (Ben-Av, Sagi, & Braun, 1992; Li et al., 2002) and the expectation to report such a grouping pattern (Mack et al., 1992; Chan & Chua, 2003) would typically make observers adopt a strategy of dividing their attentional resources so as to adequately process both stimuli in the foveal and the concurrent peripheral task. While such a division of attention may only leave a limited amount of resources available to process the peripheral stimuli, such processing of information in the "near absence of attention" has nevertheless been shown to reveal well above-chance performance in a relatively complex object-categorization task (Li et al., 2002). Overall, these previous findings are thus compatible with the current results. Our participants were explicitly told to perform a dual task, that is, to classify the central stimulus *and* search for a target in the periphery. Accordingly, one would expect that they saved at least some attentional resources for the search task, and such processing of the search items in the near-absence of attention (i.e., given only residual attentional resources) apparently sufficed to generate a reliable grouping benefit. Essentially, this grouping benefit arising on the basis of only residual attentional resources may be comparable to the effects seen in neuropsychological patients, where effective grouping was likewise found to depend on the availability of at least some attentional resources in the otherwise neglected visual field (Nowack et al., 2021; Conci et al., 2018; Gögler et al., 2016).

Across both experiments, search for the ungrouped targets revealed overall a relatively low level of performance and a comparably broad tuning of the attentional focus (as reflected in the pupil-size measures). There were also no eccentricity-dependent changes in both accuracy and pupil-size measures. A potential explanation for this absence of a modulatory effect might be that detection of this type of configuration was not facilitated by grouping processes, so that search had to be based on processing the arrangement of the individual inducer elements (Conci et al., 2007). That is, this task required a high amount of attentional resources to be performed successfully. Grouped targets, by contrast, provided a regular and simple structure requiring a much lower amount of attentional resources in order to trigger the grouping process and summon attention.

Taken together, our results thus show that part-to-whole object integration and search guidance by salient, integrated objects scale with the amount of available attentional resources. Our study also demonstrates and provides additional evidence that measurement of pupil size provides a useful method for investigating changes of the distribution of attention beyond basic variations of physical stimulus intensity.

Open practices

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in this study. No part of the study procedures or analyses were pre-registered prior to the research being conducted. However, all relevant study materials, data, and analysis code will be available on the Open Science Framework once accepted for publication.

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Declaration of Interest

The authors declare that they have no competing interests.

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2.3. RIGHT PARIETAL RTMS INDUCES BIDIRECTIONAL EFFECTS OF SELECTIVE ATTENTION UPON OBJECT INTEGRATION

The author of this dissertation designed and programmed the experiment, collected and analyzed the data, created plots and interpreted the results, and wrote the manuscript. Paul Taylor counseled and trained the author in TMS. He contributed to the interpretation of the results and critically revised the manuscript. Kathrin Finke critically revised the manuscript. Hermann J. Müller commented on and critically revised the manuscript. Markus Conci helped to design and supervise the experiment. He also contributed to the interpretation of the results and critically revised the manuscript.

Right parietal rTMS induces bidirectional effects of selective attention upon object integration

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Abstract

Part-to-whole object completion and search guidance by salient, integrated objects has been proposed to require attentional resources, as shown by studies of neglect patients suffering from right-parietal brain damage (e.g., Nowack et al. 2021). The current study was performed to provide further causal evidence for the link between attention and object integration. Healthy observers detected targets in the left and/or right hemifields, and these targets were in turn embedded in various Kanizsa-type configurations that systematically varied in the extent to which individual items could be integrated into a complete, whole object. Moreover, repetitive transcranial magnetic stimulation (rTMS) was applied over the right intraparietal sulcus (IPS) and compared to both active and passive baseline conditions. The results showed that target detection was substantially facilitated when the to-be detected item(s) were fully embedded in a salient, grouped Kanizsa figure, either a unilateral triangle or a bilateral diamond. However, object groupings in one hemifield did not facilitate target detection to the same extent when there were bilateral targets, one inside the (triangle) grouping and the other outside of the grouped object. These results extend previous findings from neglect patients. Moreover, a subgroup of observers was found to be particularly sensitive to IPS stimulation, revealing neglect-like extinction behavior with the single-hemifield triangle groupings and bilateral targets. Conversely, a second subgroup showed an opposite effect, namely an overall, IPS-dependent improvement in performance. These explorative analyses show that the parietal cortex, in particular IPS, seems to modulate the processing of object groupings by up- and down regulating the deployment of attention to spatial regions were to-be-grouped items necessitate attentional resources for object completion.

Keywords: perceptual grouping, object integration, visual attention, visual extinction, rTMS, intraparietal sulcus, parietal cortex

1. Introduction

Perceptual grouping acts to structure cluttered input from the visual environment, by integrating fragmentary visual information into coherent whole objects. One famous example that illustrates such object integration processes is the “Kanizsa figure” (Kanizsa, 1955; see Figure 1), which depicts several aligned “pacmen” inducer elements that are grouped, thereby leading to the emergence of an illusory figure (e.g., a diamond or triangle) while lacking a corresponding physical object. Kanizsa figures thus demonstrate the capability of the visual system to generate coherent wholes from fragmentary parts.

Prominent theories, such as the “feature integration theory” (Treisman & Gelade, 1980) in turn postulated that object integration arises from higher-level cognitive processes that depend on the engagement of selective attention. Conversely, several studies suggested that object integration is achieved preattentively, that is, prior to the engagement of attention, thus, supporting accounts of object-based attention (see Driver & Baylis, 1998). In this regard, a common approach to explore the relationship between selective attention and object integration is to test neurological patients with brain lesions in the right inferior parietal cortex, which often results in associated spatial attention deficits. Such selective impairments frequently lead to a condition of hemispatial neglect and associated extinction behavior (Kerkhoff, 2001; Karnath, Milner, & Vallar, 2002), which manifests in a failure to orient towards stimuli presented in the contralesional hemifield. However, despite severe inattention to one part of the visual field, these patients often show preserved access to integrated object information (Driver, 1955). For instance, Mattingley, Davis, and Driver, (1997; see also Conci, Böbel, Matthias, Keller, Müller, & Finke, 2009) presented search displays with Kanizsa-type configurations to an extinction patient and asked her to detect the removal of segments from circular disks in the left and/or right hemifield. While she was able to detect unilateral target offsets, severe extinction behavior, however, emerged when the segments were removed from both sides. In this case, the patient missed the left-sided targets and only reported the right-sided targets. However, when the cutout segments were arranged such that, they could be grouped together to form a coherent whole object across both hemifields, extinction behavior was substantially reduced, thus showing that the patient had access to the grouped object despite severe (left-sided) inattention. This finding was thus taken to suggest that object integration occurs preattentively.

By contrast, support for a crucial role of attention during object integration was recently reported in a related study by Nowack, Biel, Finke, Keller, Müller, and Conci (2021; see also Gögler, Finke, Keller, Müller, & Conci, 2016; Conci, Gross, Keller, Müller, & Finke, 2018).

They tested a sample of neglect patients in a visual search task that involved the detection of targets in the left and right hemifields. Search displays provided different configurations of Kanizsa figures that varied in their extent of perceptual grouping (Figure 1). Critically, in that study, the grouped objects were systematically varied and either only occurred in the left or right hemifield (e.g., presenting a Kanizsa triangle), or the grouping expanded across both hemifields (thus revealing a Kanizsa diamond; see Figure 1B). The results showed that when individual target segments were not grouped across hemifields, detection was compromised thus revealing extinction, as opposed to a substantially improved detection performance with a bilaterally grouped diamond configuration. Moreover, a target within a salient Kanizsa triangle presented in the attended, right hemisphere was readily detected. Likewise, the detection of a target in a salient triangle presented in the unattended, left hemifield was also rather good. The very same triangle, however, failed to improve contralesional target detection whenever it was presented together with another ipsilesional and structurally non-integrated target. This was taken to suggest that attention was captured by the salient grouped object in the unattended, left hemifield only when it was not engaged in processing the isolated target in the attended, right hemifield. These findings thus extend previous studies and show that attentional spreading from the attended to the neglected hemifield is crucial for object integration to facilitate performance.

Studies with neurological patients may provide one major source to decide between competing theories of object integration. However, the persistent impairment as a result of severe brain damage may, at the same time, lead to reorganization of the brain and could trigger specific compensatory strategies in order to cope with the lesion-related deficits (Robertson & Murre, 1999). Given this, studies with brain-damaged patients may not solely reflect the actual functions of the damaged tissue but may additionally demonstrate some lesion-specific processing (Lomber, 1999). In order to generalize from previous findings with patients, the current study used repetitive transcranial magnetic stimulation (rTMS), to induce brief and reversible disruptions in cortical functioning, thereby allowing to draw causal inferences from normal brain function in healthy observers (Walsh & Cowey, 2000). Several previous findings with TMS indeed suggest that the parietal cortex is indeed linked to attentional functioning. For instance, a study by Hilgetag, Theoret, and Pascual-Leone (2001) applied unilateral TMS over the right and left parietal cortex and observed extinction of a contralateral stimulus whenever it was presented together with a second, ipsilesional stimulus – comparable to the typical finding in neglect patients. Subject’s attention towards the ipsilesional stimuli, however, improved significantly. In general agreement with these findings, various other studies also showed that a disruption of the posterior parietal cortex can generate attentional deficits, which may be shown by failures to detect (Pascual-Leone, Gomez-Tortosa, Grafman, Always, Nichelli, & Hallett, 1994; Fierro, Brighina, Oliveri, Piazza, La Bua, Buffa, and Bisiach, 2000; Koch, Oliveri, Torriero, & Caltagirone, 2005; Ricci, Salatino, Li, Funk, Logan, Mu, Johnson, Bohning, & George, 2012) or to identify (Hung, Driver, & Walsh, 2005) targets in the visual field contralateral to the stimulation site under conditions of bilateral simultaneous presentation (Gillebert, Mantini, Thijs, Sunaert, Dupont, & Vandenberghe, 2011; see also Driver, Blankenburg, Bestmann, & Ruff, 2010; Sack, 2010, for reviews). However, it should be noted that parietal TMS stimulation not only induces neglect-like deficits in performance, but may conversely also boost visual attention both in patients (Oliveri, Bisiach, Brighina, Piazza, La Bua, Buffa, & Fierro, 2001; Brighina, Bisiach, Oliveri, Piazza, La Bua, Daniele, & Fierro, 2003; Agosta, Herpich, Miceli, Ferraro, & Battelli, 2014) and in healthy volunteers (Hilgetag et al., 2001; He, Lan, Xu, Mao, Chen, Huang, & Pei, 2013; Xu, Lan, Zhang, Liu, He, & Lin, 2016; for a review see Yeager, Dougher, Cook, & Medaglia, 2021). Moreover, it is commonly reported that theta-burst stimulation causes a high interindividual variability due to for example different brain plasticity (Hordacre, Goldsworthy, Vallence, Darvishi, Moezzi, Hamada, et al., 2017; Corp, Bereznicki, Clark, Youssef, Fried, Jannati, Davies, et al., 2020). Together, these findings thus demonstrate a causal involvement of the parietal cortex in spatial attentional orienting, while the TMS stimulation may eventually induce performance costs and benefits.

The current study was performed to further test the causal role of selective attention for object integration, and to extend previous findings reported with neglect patients to healthy observers. Accordingly, we made use of offline rTMS and stimulated the right intraparietal sulcus (IPS). In the experiment, a sample of healthy participants would be presented on a given trial (see Figure 1A) with a search display that contained four disks, and the task was to indicate whether segments were removed from the left disk, the right disk, from the disks on both sides or not at all. Variations of the orientations of the removed segments in turn generated different variants of an illusory figure comparable to the stimulus configurations presented in Nowack et al. (2021): a whole Kanizsa "diamond" spreading across both hemifields and a Kanizsa "triangle" confined to only one hemifield. This allowed an assessment of whether parietal stimulation modulates target detection performance in the two visual hemifields (ipsi- and contralateral to the critical rTMS stimulation over area IPS). Importantly, since several studies reported that various forms of masking can substantially reduce the visibility of Kanizsa figures (Sobel & Blake, 2003; Harris, Schwarzkopf, Song, Bahrami, & Rees, 2011; Schwarzkopf & Rees, 2011; Moors, Wagemans, van Ee, de-Wit, 2015; Banica & Scharzkopf, 2016), we included a cluttered postmask after the presentation of the stimulus display in order to decrease the visibility of the target stimuli, hence making it a harder task for the healthy participants (for a review see Haynes, 2009). Each participant completed three experimental sessions, thereby varying the type of TMS stimulation that was applied (IPS - experimental, M1 – active baseline, no rTMS - passive baseline). We expected IPS transcranial magnetic stimulation to explicitly influence the selection of (grouped) objects.

2. Materials and Methods

2.1. Participants

17 participants (7 males, *M* = 25.7 years, *SD* = 3.9 years) with normal or corrected-to-normal vision took part in the experiment. Participants either received monetary compensation (10 Euro per hour) or course credits for taking part in the experiment. The experimental procedure was approved by the local ethics committee (Department of Psychology, Ludwig-Maximilians-University, Munich), and written informed consent according to the Declaration of Helsinki was obtained from all participants.

Sample size was determined on the basis of an a-priori power analysis. We aimed for 95% power to detect an $f(U)$ effect size of 1.08 (partial $\eta^2 = .54$) at an alpha level of .05 and a nonsphericity correction of 1. This effect size was determined on the basis of previous studies, which used comparable stimuli and tasks (Chen, Weidner, Zeng, Fink, Müller, & Conci, 2020). A TMS-dependent modulation of attention and concurrent object integration processes in the current experiment would be reflected in a significant 3-way interaction [Configuration x Target x TMS-stimulation], which – according to our analyses – would require only 6 participants in a within-subjects design. However, effects of TMS upon visual processing and attention are typically rather varied across participants and previous studies therefore typically used larger sample sizes (e.g., Fierro et al., 2000; Brighina et al., 2003; Battelli, Alvarez, Carlson, & Pacual-Leone, 2009). Given this, we decided to test a larger sample size with a total of N=17 participants[1].

[1] It should be noted that we initially tested N=20 participants but three participants had to be excluded from the data proper because they performed well below chance level in the (important) bilateral target displays in the IPS (*M* = 16.5%), the M1 (*M* = 11.5%) and the no rTMS (*M* = 16.9%) stimulation conditions (all other participants were much more accurate in responding to bilateral targets across the various stimulation conditions, *M* = 88.7%). Hence, the results reported here are based on a sample of 17 participants (which is still well above the minimal sample size as suggested by our power calculations reported above).

2.2. Apparatus and Stimuli

The experimental routine was programmed using the Psychophysics toolbox (Kleiner, Brainard, & Pelli, 2007) in combination with Matlab (MATLAB, 2017). The experiment was conducted in a sound-attenuated room that was dimly lit. During the experiment, the head of the participant was stabilized by a forehead and chin rest, positioned 57 cm from a 17-inch monitor (1024 x 768 pixels screen resolution, 85-Hz refresh rate). Eye movements were recorded from the right eye at a sampling rate of 250 Hz using an Eyelink CL eye tracker system (SR-Research Ltd., ON, Canada). At the beginning of each block, a 5-dots calibration routine was performed. To ensure that observers remained fixated at the screen center, the eye gaze was monitored, and a given trial was discarded if participants moved their gaze more than 1.3° away from the central fixation cross, thus, revealing an overt orienting response. This was the case in 9.6% of all trials.

Stimuli were the same as used in the study by Nowack et al. (2021) and consisted of four gray disks (3.81 cd/m2), each subtending a diameter of 1º of visual angle. The stimuli were presented against a black background (0.01 cd/m2). The disks were arranged in diamond form subtending 3.5º x 3.5º, and their distance from the central fixation cross was 1.3º. Each trial started with the presentation of a premask display (with complete, circular placeholder disks), followed by a briefly presented search display where segments were cut out from the placeholders, thus revealing various Kanizsa-type stimulus configurations (see the supplementary Figure S1 for all possible arrangements). Subsequent to the search display, a densely cluttered postmask display was presented that consisted of 9 large and 4 small disks with removed segments, depicting variable orientations of the cut-out parts. The postmask only presented arrangements where the individual segments would not give rise to an illusory figure (see Figure 1A for an example of the postmask stimulus). There were four different types of search display: *unilateral* left displays consisted of two central disks (one above and one below fixation) and the disk to the left of fixation, which all had a segment cut out whereas the right disk was complete (i.e., without cut-out section); in *unilateral* right displays, segments were removed from the right and the central disks, and the left disk was complete. In *bilateral* displays, all four circles were presented with cut-out (quarter) segments. Finally, in catch trials, only the central (i.e., the top and bottom) disks had cut-out sections, whereas the left and right disks were both complete. Note that catch trials were presented to obtain a measure for guessing. Examples of all four types of search display are depicted in Figure 1A.

For each of these search display types, four variants of object groupings were generated through systematic changes of the orientation and size of the cut-out segments (see Figure 1B for examples of these types of object groupings in bilateral target displays). For the diamond configuration (Figure 1B, right), the segmented disks were arranged such that a complete Kanizsa-type illusory diamond emerged across both hemifields from the inward-facing indents in the disks (Chen, Glasauer, Müller, & Conci, 2018). In addition, two variants of this configuration presented a complete Kanizsa-type illusory triangle, either in the right hemifield (right triangle, Figure 1B, middle-right), or in the left hemifield (left triangle, Figure 1B, middle-left). Note that the cutout segment in the other hemifield was presented such that it did not integrate with the triangle, facing randomly either the top or bottom. Finally, ungrouped configurations were arranged pseudo-randomly such that no illusory figure emerged within the left or the right hemifield: the disks with missing quarter-segments on the left and right faced up and down, and the cut-out segments in the top and bottom disks faced to the left and right, respectively (see Figure 1B, left).

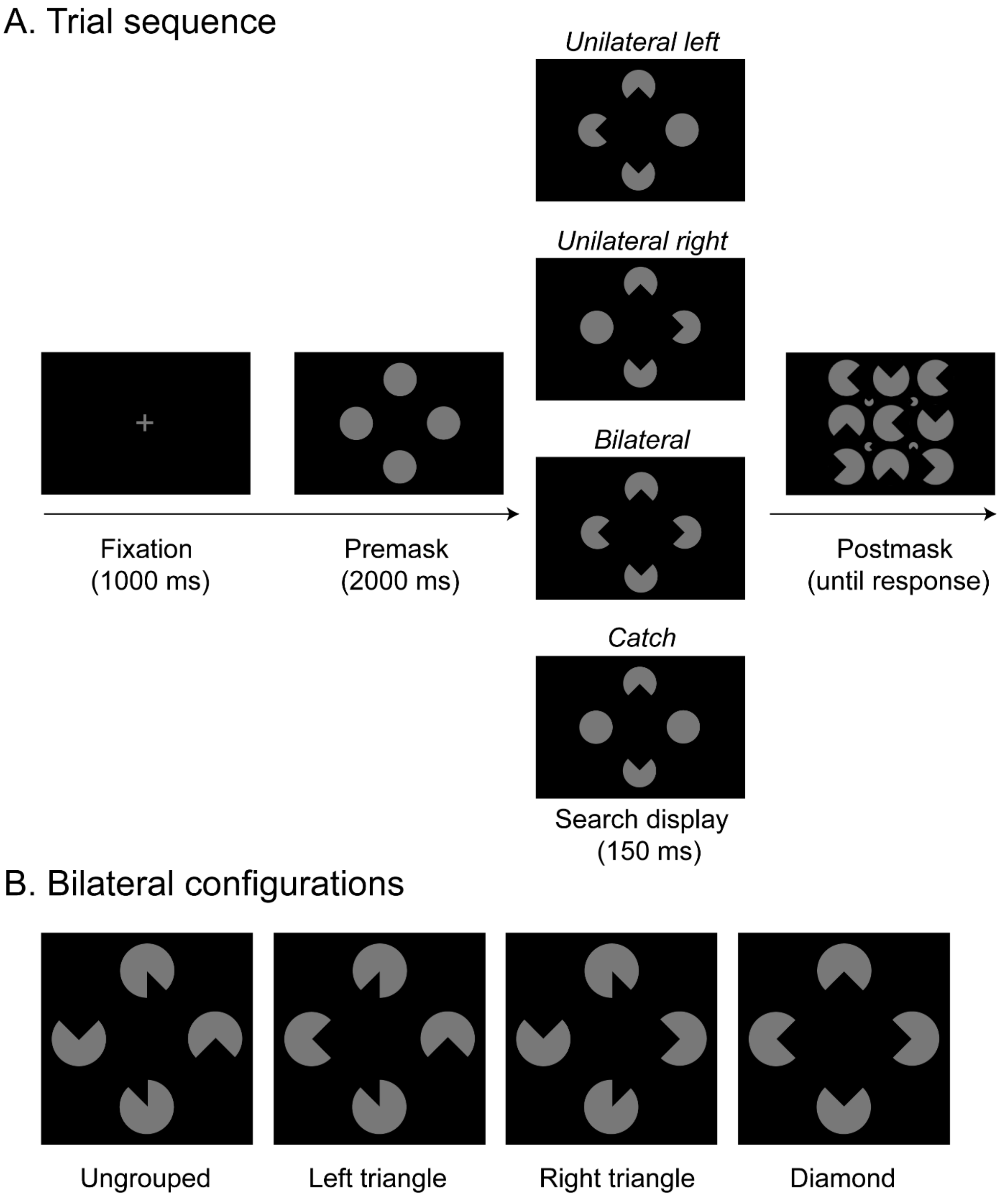

Figure 1. (A) Example trial sequence. First, a fixation cross was shown for 1000 ms, followed by a premask display presented for 2000 ms. Next, participants saw a Kanizsa-type configuration which was shown for 150 ms with quarter segments removed from the top and bottom, and from either the left side (unilateral left), the right side (unilateral right), both sides (bilateral), or no side (catch), as depicted in the example search displays from top to bottom, respectively. Finally, a postmask display (with nine big and four small disks arranged in random orientation) was presented until a response was given. In the example trial sequence, search displays present possible variants of a diamond configuration. (B) Examples of the

four different types of object groupings presented in bilateral trials (i.e., displays containing target cut-out segments in both hemifields): In the diamond configuration, a complete illusory figure spanning across both hemifields was visible (right panel). The right triangle condition (middle-right panel) presented an illusory triangle confined to only the right hemifield, and in the left triangle condition (middle-left panel) an illusory triangle emerged in only the left hemifield. The ungrouped configuration (left panel), which did not lead to the emergence of any illusory figure, served as a baseline.

2.3. Procedure and Behavioral task

The experimental procedure was adopted from the study by Nowack et al. (2021): Each trial started with the presentation of a fixation cross at the center of the screen for 1000 ms. This was followed by a premask display, which presented four complete disks in a diamond arrangement around fixation for 2000 ms. Next, the search display presented one of the four possible object configurations (see examples of bilateral displays in Figure 1B). In the search display, segments were removed from the top and the bottom and from either the left side, the right side, both sides, or from neither left nor right side (see Figure 1A). Thus, zero to two segments were removed from the left and right circles, and these served as the to-be-detected targets, whereas the two segments on the top and bottom were response-irrelevant distractors. The search display was presented for 150 ms. The optimal presentation time of the search display was determined prior to the main experiment in a separate pilot study, which tested a group of 11 participants and compared various presentation times with the aim to achieve an overall accuracy of around 80%. Subsequent to the search display, a postmask appeared, displaying 9 large and 4 small disks with removed segments, with variable orientations of the cut-out parts (note that the orientations of the segments in this postmask were arranged such that they would not induce an illusory figure or a grouped object). The postmask was shown until the participants indicated on which side(s) a target segment was removed from the search display via keyboard press (four response alternatives: left [key 1], right [key 2], both [key 3], or none [key 4]). Each trial was separated from the next by a blank screen (with central fixation cross), which was shown for 1000 ms. Figure 1A presents an example trial sequence and possible target types presented in the search displays, illustrating where the cut-out segments could be removed from a given configuration.

A given session of the experiment consisted of 288 experimental trials, which were presented in eight blocks of 36 trials each, with a break after each block. Each block consisted of 8 unilateral left, 8 unilateral right, 16 bilateral, and 4 catch trials, presented in a randomized order. The various types of object configuration (ungrouped, left triangle, right triangle, or diamond) were presented in randomized order across the whole experiment. Each participant completed three experimental sessions (on three separate testing days), where each session would be identical in terms of the experimental setup, except for the type of TMS stimulation that was applied (IPS - experimental, M1 – active baseline, no rTMS - passive baseline, see further details below). All three experimental sessions (with each of the TMS stimulation conditions) were administered in counterbalanced order and participants were not told which condition was applied. In summary, the experiment varied three experimental factors: object configuration (ungrouped, left triangle, right triangle, or diamond), target (unilateral left, unilateral right, bilateral, catch) and TMS stimulation (IPS, M1, no rTMS).

2.4. Transcranial Magnetic Stimulation

We applied continuous theta burst rTMS triplets of pulses at 50 Hz (presented in bursts at 5 Hz, intensity = 80% active motor threshold, duration = 40 seconds, i.e., 600 pulses) by using a figure-8 coil (PowerMAG research 100 machine with a coil with an outer winding diameter of 95 mm, MAG & More GmbH, Germany). TMS was applied offline at the beginning of each of the three experimental sessions. In each session, the TMS stimulation would be applied either (i) applied to the target site (IPS), (ii) applied to an M1 control site (active baseline), or (iii) would not be applied, (passive baseline, no rTMS). Coil positioning used a neuronavigation system via frameless infrared stereotactic registration (Brainsight, Rogue Research, Canada) to determine the stimulation sites based on the participant's T1 weighted structural MRI scans.

Based on the study of Vandenberghe and colleagues (2012) who found contralateral effects in a brain-lesioned patient, we chose the target site on the rendered surface of the structural scan on the medial bank of the IPS. To preferentially target more posterior regions analogous to IPS0/1/2 (thought to be particularly important for the allocation of visual spatial attention to the contralateral hemifield; for a review see Gillebert et al., 2011) and to allow consistent targeting across participants based on neuroanatomical features, we selected the portion of the medial bank of the IPS immediately dorsal to where the middle IPS segment branched off to become what is referred to as the posterior segment of the IPS (Vandenberghe et al., 2012), which usually follows a descending route and becomes the intraoccipital sulcus (Duvernoy, 1999). This site was therefore in the most posterior part of the superior parietal lobe before reaching the occipital lobe. MNI coordinates (see Figure 2A) were similar (within 10 mm) to the coordinates [x=21, y=-78, and z=43] reported in Mars et al. (2011) and Gillebert et al. (2011) for a more ventral portion of the medial bank of the posterior IPS.

For the active baseline condition, we searched for the M1 region functionally (Figure 2B). This control site was selected as it allowed a similar sensation of being stimulated given that approximate laterality (x=41) and dorsa-ventral (z=51) were approximately equivalent to the active site. It should be noted that there was no significant difference in mean stimulation intensity between the IPS and M1 stimulation conditions, $t(16) = 0.61$, $p = .553$ (mean intensity = 44.6% and 44.5% maximal stimulator output for IPS and M1 stimulation conditions, respectively).

In the passive baseline condition, the coil was positioned orthogonally to the participant's scalp such that no effective stimulation could reach the underlying brain tissue. This passive baseline condition was used to control for nonspecific clicking sound and tactile sensation of the TMS pulses (Marzi et al., 1998). The order of the TMS stimulation conditions was counterbalanced across participants.

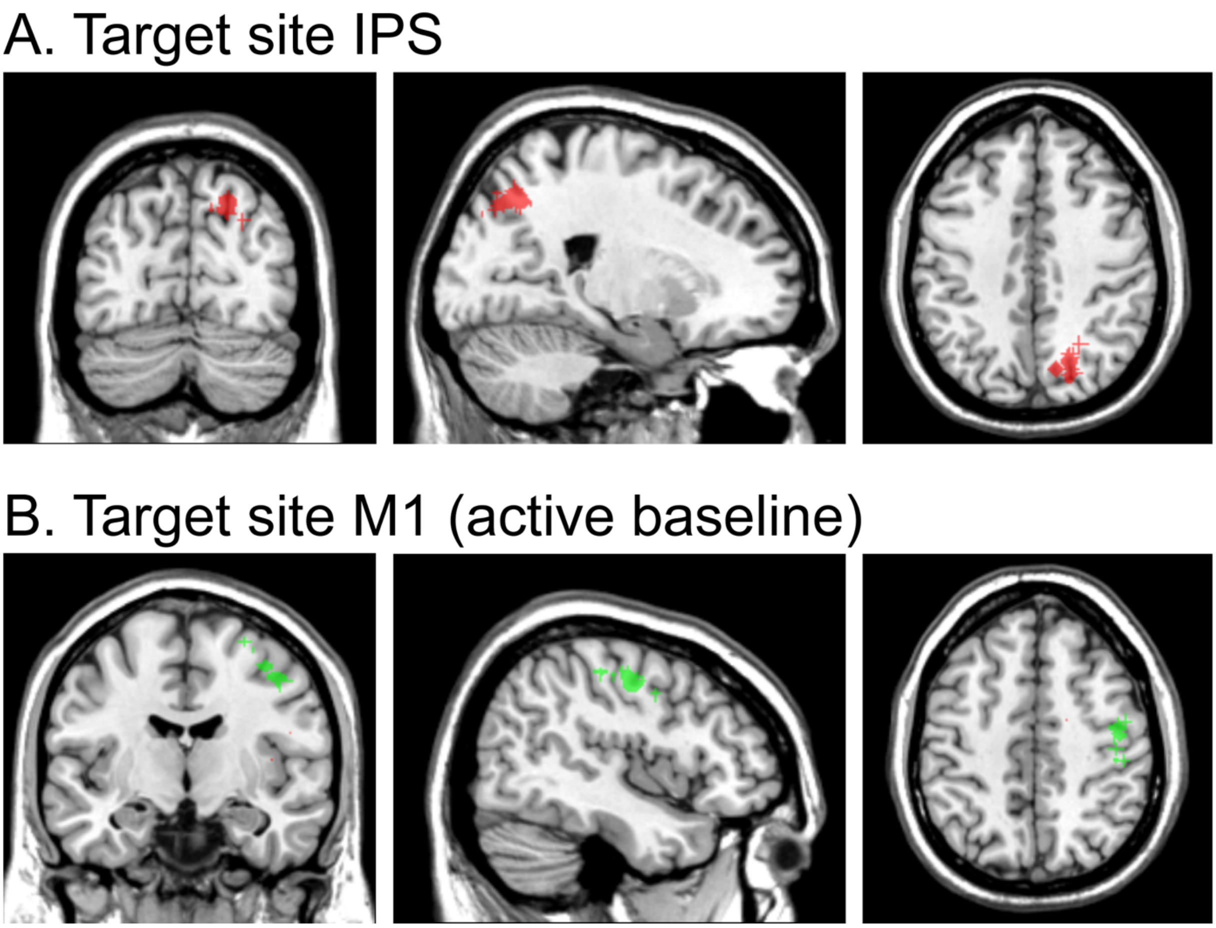

Figure 2. Individual, MRI-guided TMS target sites for all participants. (A) Target site in the IPS with the associated mean MNI co-ordinates [20, -69, 44]. (B) Target site M1 as used in the active baseline condition, with the associated mean MNI coordinates [41, -10, 51].

3. Results

Statistical analyses were performed using repeated-measures analyses of variance (ANOVAs) and subsequent post-hoc tests (paired-samples t-tests with Holm correction for multiple comparisons) with the program R Studio (RStudio Team, 2015). Greenhouse–Geisser corrected values are reported when Mauchley's test of sphericity was significant ($p < .05$).

An initial analysis was performed to estimate the overall level of guessing, by performing a repeated-measures ANOVA on catch trials (i.e., trials without a target but with varying distractors) with the within-subject factors object configurations (ungrouped, left triangle, right triangle, diamond) and TMS stimulations (IPS, M1, no rTMS). The results showed that participants' performance on trials without a target was very accurate overall (79.6%), thus meeting the intended criteria of 80% accuracy in overall task performance (e.g., as established in a previous pilot experiment, see methods). The ANOVA did not reveal any significant main effects or interactions (all F's < 1.78, all p's > .05). The catch-trial accuracies therefore show that participants were able to perform the task without relying too much on guessing responses.

Next, we compared the various types of targets in an overall repeated-measures ANOVA on the detection accuracies (but now excluding the catch trial responses) with the factors object configuration (ungrouped, left triangle, right triangle, or diamond), target (unilateral left, unilateral right, bilateral) and TMS stimulation (IPS, M1, no rTMS). This analysis revealed a significant main effect of object configuration, $F(1.95, 31.20) = 3.53$, $p = .042$, $\eta^2 = .01$, showing somewhat higher accuracies in ungrouped (91.7%) than in diamond (89.5%), left triangle (88.6%) and right triangle (87.9%) configurations, alongside with a highly significant 2-way interaction of object configuration by target, $F(3.72, 59.52) = 11.03$, $p < .001$, $\eta^2 = .06$. There were no other significant main or interaction effects in this overall ANOVA (all p's > .05; see the supplementary Figure S2 for an overview).

To decompose the significant 2-way interaction, additional analyses were performed to compare the various object configurations, separately for the three different types of targets (unilateral left, unilateral right, bilateral). First, for unilateral left targets (mean correct detections: 90.6%), there was a significant main effect of object configuration, F (1.92, 30.72) = 8.93, $p < .001$, $\eta^2 = .07$ (see Figure 3A). Holm *post-hoc* tests revealed detection accuracies to be (marginally) higher with left triangle configurations (96.2%) than ungrouped configurations, $t(16) = 2.37$, $p = .063$, as well as right triangle and diamond configurations, $t(16)$'s > 3.24, all p's < .021. Accuracies for ungrouped configurations were also higher (92.3%) compared to right triangle (86.8%) and diamond (87.3%) configurations, $t(16)$'s > 2.93, all p's < .029. Detection accuracies between right triangle and diamond configurations were comparable, $t(16) = 0.28$, $p = .786$. This pattern of results indicates that the emergence of a salient triangle in the left hemifield substantially facilitates left sided, unilateral target detection.

Next, a comparable pattern was also revealed with unilateral right targets (see Figure 3B; mean correct detections: 88.7%), where a comparable ANOVA also resulted in a significant main effect, F (2.01, 32.16) = 7.03, $p = .003$, $\eta^2 = .09$. Detection accuracies were significantly higher with right triangle configurations (94.2%) as compared to all other configurations, $t(16)$'s > 3.26, all p's < .019. Moreover, the ungrouped configuration was again somewhat higher in accuracy (89.0%) than the left triangle configuration (84.0%), $t(16) = 2.70$, $p = .047$. All other comparisons showed no significant difference (diamond configuration: 87.4%), all $t(16)$'s < 2.70, all p's > .05. Thus, this result pattern for unilateral right targets mirrors the results for the unilateral left targets and once again demonstrates that a salient object configuration in the target hemifield can substantially enhance (unilateral) detection accuracies.

Finally, for bilateral targets (mean correct detections: 88.7%) the main effect of configuration was also significant, F (1.74, 27.84) = 11.15, $p < .001$, $\eta^2 = .08$ (see Figure 3C). Accuracies were higher in ungrouped (92.9%) and diamond configurations (93.7%) as compared to the left triangle (84.9%) and right triangle (82.4%) configurations, all $t(16)$'s > 3.68, all p's < .006. Moreover, both ungrouped and diamond configurations and left and right triangle configurations were comparable to each other, $t(16)$'s < 0.92, $p > .739$. This shows that the detection of the bilateral targets was hampered whenever a non-integrated but task-relevant target was presented simultaneously with a target embedded in a salient triangle Kanizsa figure in the other hemifield. Compared to the two search displays with a triangle configuration, the ungrouped and diamond configurations resulted in higher accuracies, which possibly resulted from attention being spread more equally across the whole display.

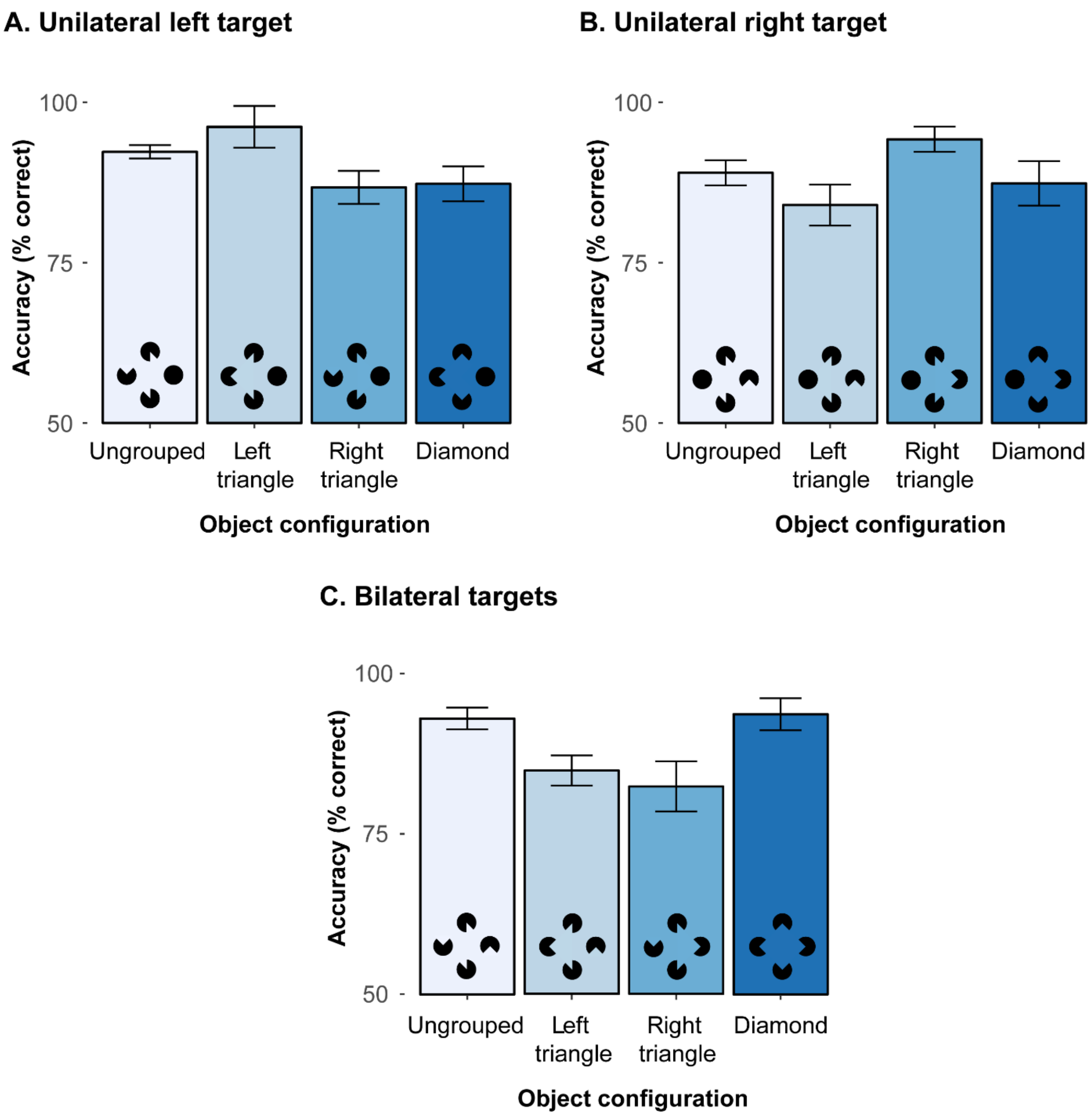

Figure 3. Mean percentages of correct detections (with associated within-subject 95% confidence intervals) as a function of object configuration (ungrouped, left triangle, right triangle, diamond) for (A) unilateral left, (B) unilateral right and (C) bilateral targets.

Together, these results show that salient object groupings modulate attentional selection: When the target(s) coincide with the grouped structure, detection performance is improved, while performance is conversely impaired when the salient grouping does not comprise all task-relevant targets. In this latter case, the salient grouping presumably attracts attentional resources that are then missing to process the target in the non-salient parts of the display. While this pattern of results essentially corresponds to the findings reported by Nowack et al (2021) in neglect patients, the concurrent TMS stimulation in area IPS did not yield any significant effects. However, as discussed above, parietal TMS stimulation might not necessarily lead to impaired attentional processing but could also result in an up-modulation of processing, which might then lead to an improvement in performance potentially due to different brain plasticity and thus interindividual variability (see Introduction section). These opposing effects of TMS might thus cancel each other to some extent across different observers and were consequently further examined in a series of explorative follow-up analyses. To this end, we calculated the mean performance across all bilateral trials per participant in the M1 stimulation condition (active baseline) and subtracted it from the mean performance across bilateral trials in the IPS stimulation condition. Out of the complete sample of 17 participants, a subgroup of N=7 participants showed an overall reduction in bilateral detection accuracy (of 7.14%) in the IPS, as compared to the M1 stimulation condition ("IPS-cost" subgroup). A second subgroup of the remaining N=10 participants conversely revealed an overall benefit in performance (of 7.16%) in detecting bilateral targets in the IPS as compared to the M1 TMS stimulation condition ("IPS-benefit" subgroup).

The specific variations of performance in these two subgroups were subsequently analyzed in a series of comparisons. It should be noted that, for these analyses, we merged the data from (i) the "left triangle" and the "right triangle" configurations into a single "triangle" condition, and we also combined (ii) unilateral left and right targets to a single "unilateral" target condition. The data were combined in order to increase the number of observations per condition and because the above reported analyses already revealed comparable and "symmetric" effect patterns (e.g., comparable benefits in detecting the unilateral targets in both left and right triangle conditions). In a first step, a mixed 3-way ANOVA with the between-subject factor subgroup (IPS-cost, IPS-benefit), and the within-subject factors target (unilateral, bilateral) and configuration (ungrouped, triangle, diamond) was computed for the no rTMS stimulation condition in order to explore the possibility that the two subgroups already differed without applying any TMS stimulation. This analysis yielded no significant main effects or interactions, including the factor subgroup, all *F*'s > 0.17, *p's* < .05, thus showing that the two groups were per se comparable, and the different result patterns thus must have emerged from the TMS stimulations.

Next, performance in the "IPS-cost" subgroup was analyzed with a 2-way repeated-measures ANOVA. We found a significant interaction between object configuration (ungrouped, triangle, diamond) and TMS stimulation (IPS, M1) in bilateral targets, $F(2, 12) = 5.34$, $p = .022$, $\eta^2 = .02$ (see Figure 4A, left). In triangle configurations, the mean accuracy was reduced by 13.9% with IPS stimulation (76.2%) as compared to the M1 stimulation

(90.1%), $t(6) = -2.41$, $p = .026$, whereas there was no significant difference (of 3% and 1.5%) across the TMS stimulation conditions in ungrouped or diamond configurations, respectively, all t's (6) < 1.11, p's > .05 (one-tailed). This pattern shows the IPS stimulation had a rather specific cost of processing bilateral targets, which becomes particularly evident in triangle configurations. That is, the participants in the "TMS-cost" subgroup tended to miss one of the bilateral targets when the display configuration was biased, thus revealing one salient target (i.e. the triangle) and a second, less salient target item. By contrast, for unilateral targets (see Figure 4A, right), the results showed no significant main or interaction effects, all F's < 2.27, $p > .05$.

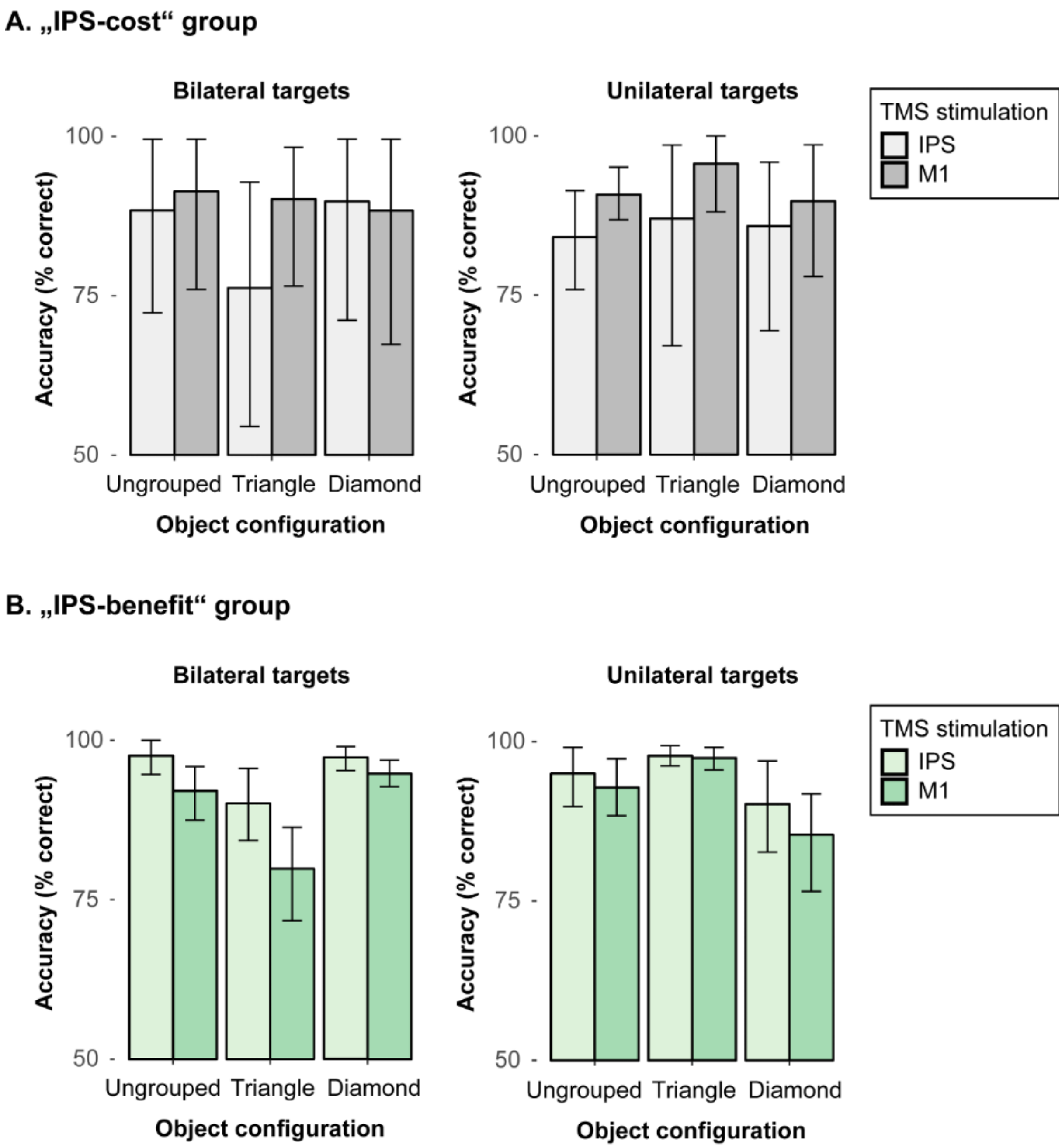

Figure 4. Mean percentages of correct detections (and associated 95% confidence intervals) as a function of object configuration (ungrouped, triangle, diamond) in the IPS and M1 TMS stimulation conditions. The results are depicted for the "IPS-cost" (A) and "IPS-benefit (B) subgroups for bilateral target displays (left panels) and for unilateral target displays (right panels).

In a final step, we then analyzed performance in the "IPS-benefit" subgroup, that is, in those individuals that benefited overall from the IPS stimulation (relative to M1 stimulation). A repeated-measures ANOVA of the mean detection accuracies for bilateral targets with the factors object configuration (ungrouped, triangle, diamond) and TMS stimulation (IPS, M1) showed a significant main effect of object configuration, F (2, 18) = 10.42, $p < .001$, $\eta^2 = .31$, revealing reduced accuracies for the triangle (84.9%) as compared to ungrouped (94.8%) and diamond (96.1%) configurations, t's (9) > 4.00 p's < .001. The main effect of TMS stimulation was also significant, F (1, 9) = 16.86, $p = .003$, $\eta^2 = .15$, with overall higher accuracies for IPS (94.9%) than M1 (88.9%) stimulation. Moreover, the 2-way interaction was also significant, F (2, 18) = 3.87, $p = .040$, $\eta^2 = .04$ (see Figure 4B, left), revealing higher detection accuracies for the IPS than M1 stimulation in ungrouped (IPS: 97.6%; M1: 92.1%) and triangle configurations (IPS: 90.1%; M1: 79.9%), all t's (9) < 2.46, p's < .036, as opposed to no reliable difference with diamond configurations were performance was overall close to ceiling and thus only showed a marginal benefit with IPS stimulation relative to the M1 stimulation (IPS: 97.3%; M1: 94.8%), t (9) = 2.06, $p = .071$ (one-tailed). In addition, the results for unilateral targets only showed a significant main effect for object configurations, F (2, 18) = 7.16, $p = .005$, $\eta^2 = .18$ (see Figure 4B, right), showing reduced accuracies for the (incomplete) diamond (87.8%) as compared to ungrouped (93.9%) and triangle (97.6%) configurations, all t's (9) > 2.81 p's < .011. There were no further main or interaction effects that involved the factor TMS stimulation, all F's < 4.21, $p > .05$. This pattern suggests that for the IPS-benefit subgroup, IPS stimulation improved the detection accuracies of the bilateral target displays in particular in ungrouped and triangle configurations, suggesting that IPS stimulation – in this subgroup –enhanced the spreading of attention across both hemifields.

4. Discussion

The present study investigated whether the posterior parietal cortex mediates the attentional selection of target items and the concurrent organization of the display layout according to perceptual grouping mechanisms. To this end, a sample of healthy participants was stimulated with rTMS over the medial bank of the IPS (as compared to an active, M1, and a passive, no-rTMS, control condition), while performing a target detection task with briefly presented (and subsequently masked) visual search items, that allowed us to compare object integration processes in the left and right visual hemifields. The task required participants to detect lateral targets, which were embedded into different variants of groupings such that individual parts could be integrated into coherent Kanizsa-type illusory objects within the left, the right, or across both visual hemifields.

The results showed that the detection of unilateral targets was enhanced in accuracy when the individual items in the display could be grouped together to form an illusory triangle configuration (that also embedded the target). This result is in line with previous studies who found that salient object groupings tend to capture attention (see e.g. Rauschenberger & Yantis, 2001; Senkowski et al., 2005; Wiegand et al., 2015; Kimchi et al., 2016).

Interestingly, the very same salient triangle configurations within a given hemifield resulted in poorer search performance when there were bilateral, as opposed to unilateral, targets (83.6% vs. 95.2%, t's $(16) > 5.46$, p's $< .001$). That is, participants appeared to have missed the non-integrated target when it appeared together with a target embedded in the salient triangle in the other hemifield, suggesting that attention is biased towards the salient grouped structure. By contrast, no comparable reduction in performance was evident for ungrouped and diamond configurations, presumably, because in these configurations, attention was not biased towards one side and could therefore spread equally across the whole display. This pattern is largely comparable to the neglect patient's results as reported in the study by Nowack et al. (2021): when attention is currently engaged in one half of the display, other objects are likely to be missed. However, if attention is available, then grouping can increase the conspicuity of a given target, thereby enhancing search efficiency, and improving its detectability (Conci, Müller & Elliot, 2007; Conci, Töllner, Leszczynski, & Müller, 2011; Wiegand et al., 2015; Nie, Maurer, Müller, & Conci, 2016). Importantly, unlike neglect patients, our healthy participants in the current study were able to spread attention equally across both hemifields, suggesting in turn that attention was available to bind fragmentary parts into a coherent whole in the first place, thus triggering the formation of an integrated object (see Nowack et al., 2021). This result is also consistent with findings from several masking studies who reported that the integration of separate elements into a coherent whole illusory object is hampered when awareness is unavailable to bind parts to a coherent whole object (Sobel & Blake, 2003; Harris, Schwarzkopf, Song, Bahrami, & Rees, 2011;

Schwarzkopf & Rees, 2011; Moors, Wagemans, van Ee, de-Wit, 2015; Banica & Scharzkopf, 2016).

While the current results are in general compatible with the view that object grouping requires attention, an effect of the TMS stimulation in parietal cortex did not reveal any effect (at least when considering the entire sample of observers). This lack of a modulatory influence could be related to the high variability of the neglect syndrome, which is typically caused by fairly large and variable, right-sided lesions in parietal regions, while extending into temporal, occipital, frontal cortex, and may even propagate into subcortical structures (Vallar & Perani, 1986; Kerkhoff, 2001; Karnath et al., 2002), while the severity of behavioral symptoms may also vary quite substantially across individuals depending on the location and size of the lesion (Kerkhoff, 2001; Sack, 2010). Thus, quite a diverse range of lesions may lead to diverse clinical signs of neglect. Moreover, studies that examined neglect-like symptoms with TMS also varied quite substantially in terms of the specific areas in parietal cortex which were stimulated (e.g., Pascual-Leone et al., 1994; Fierro et al., 2000; Hung et al., 2005; Koch et al., 2005; Ricci et al., 2012; Donaldson, Rinehart, & Enticott, 2015; see also Driver et al., 2010; Sack, 2010, for reviews). A number of these studies targeted the posterior parietal cortex by using an EEG coordinate system, leading to stimulation co-ordinates varying across the angular gyrus, intraparietal sulcus in the superior parietal lobule to the temporoparietal junction (Ricci et al., 2012; Donaldson, Rinehart, & Enticott, 2015). Finally, parietal TMS was found to not only inhibit attentional processing, thus leading to costs in performance (Pascual-Leone et al., 1994; Fierro et al., 2000; Hung et al., 2005; Koch et al., 2005; Gillebert et al., 2011; Ricci et al., 2012; see also Driver et al., 2010; Sack, 2010, for reviews) but to also reveal excitatory effects that result in an improvement in performance (Oliveri et al., 2001; Brighina et al., 2003; He at al., 2013; Agosta et al., 2014; Xu et al., 2016; for a review see Yeager et al., 2021). In light of this large variability in terms of the specific functional localization and the resulting effects upon attention, it may actually not be surprising that our overall analysis revealed no TMS-specific effect. We therefore not only analyzed the grand averages across all participants, but also focused on an exploratory analysis on individual effect patterns. However, some limitations should be acknowledged. For instance, when interpreting the results, one should consider the post-hoc nature of our exploratory (group-wise) TMS analysis, which was partly motivated by the lack of an overall, modulatory influence of the parietal rTMS stimulation upon object completion. Future studies with a directed hypothesis would therefore be necessary to confirm our exploratory findings. Moreover, spatial-attentional deficits are also commonly associated with a larger damage of the intraparietal lobule (IPL), which also extends into IPS (Molenberghs et al., 2008). Future studies should therefore try to not only stimulate IPS but also portions of IPL (e.g., as reported in a clinical study by Gillebert et al., 2011).

That being said, our follow-up analyses resulted in one subgroup (N=7), who showed an "IPS-cost", that is, TMS stimulation in the target area IPS had a negative effect on accuracy, as compared to M1 stimulation. This IPS-cost in performance, however, was only evident when observers were presented with bilateral targets (i.e., a condition which would typically result in extinction behavior in neglect patients), and when being presented with triangle configurations (where the salient triangle would induce an attentional bias towards one hemifield). Bilateral detections in these displays showed substantially reduced accuracies subsequent to IPS stimulation (76.2%) as compared to M1 stimulation (90.1%). No comparable difference was observed for the other two types of bilateral configurations (ungrouped, diamond), when comparing the two TMS stimulations (ungrouped - IPS: 88.4%, M1: 91.4%; diamond - IPS: 89.8%, M1: 88.4%). Moreover, no significant differences across TMS stimulation sites were evident in this subgroup when processing unilateral targets (IPS: 85.7%, M1: 92.1%). It thus seems that the participants in this subgroup established a neglect-like extinction behavior after right-parietal TMS stimulation: they tended to miss one of two bilateral targets (see e.g., Nowack et al., 2021). That is, the typical bias in neglect patients to only attend to single target items (in their attended field) is mirrored in the healthy observer's performance after IPS stimulation. Moreover, the grouped, and thus salient target did not seem to be selected at the expense of the other, ungrouped, and thus less salient target (error probabilities: 4.73% for the non-salient vs. 4.46% for the salient targets). Rather, the targets in these triangle displays were overall more likely to be missed when presented in the left hemifield (error probability: 6.77%) as compared to the right hemifield (2.92%). This shows the right-parietal IPS stimulation in this subgroup indeed resulted in a specific disadvantage of detecting the left-sided target in bilateral displays, which is comparable to the typical extinction behavior seen in neglect patients.

Opposite to this pattern, a second subgroup (N=10) showed an "IPS-benefit", that is, in these observers, the IPS stimulation had a positive effect on the detection accuracies, as compared to the stimulation of M1. These participants showed more accurate detections of bilateral targets subsequent to IPS, as compared to M1 stimulation for all three types of configurations (94.9% vs. 88.9%). Thus, in this subgroup, the IPS stimulation seems to have facilitated the spreading of attention across both hemifields, thus improving performance overall. This finding might be explained by some inter-hemispheric imbalance, which would assume that not the absolute level of activity within the attentional network likely causes a selection bias, but rather the ratio of neural activity allocated to selection processes in both hemispheres (Kerkhoff, 2001; Sack 2010). For instance, it has been shown that stimulation of the parietal cortex in the unimpaired hemisphere of neglect patients may reverse this cerebral imbalance, which in turn reduces extinction behavior (see e.g., Agosta et al., 2014). In the current subgroup of healthy participants, the IPS stimulation might likewise have "optimized" the cerebral balance in the attentional network. Hence, our IPS stimulation resulted in an overall enhancement of performance with bilateral targets in this subgroup.

In summary, our results extend previous findings from neglect patients and show that the parietal cortex plays a crucial role in mediating the attentional selection of integrated objects. The intraparietal sulcus thus seems to play a role in processing salient, grouped objects, by allocating attentional resources to to-be grouped items in space (Mars et al., 2011; Vandenberghe et al., 2012).

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3. GENERAL DISCUSSION

The goal of this dissertation was to systematically investigate the role of visual selective attention for object integration, thereby supporting recent preliminary results suggesting attention to be an integral part for perceptual grouping processes (i.e., Gögler et al., 2016; Conci et al., 2018) and extend them to healthy subjects.

The first section of the General Discussion highlights the main findings and presents conclusions we have drawn from each individual project. The second section then attempts to combine all results and discusses the key implication across all projects. A discussion of methodological considerations follows and finally, the main scientific progress of this thesis is summarized.

3.1. MAIN FINDINGS OF EACH PROJECT

3.1.1. PROJECT 1

In this first research project of my thesis, we tested the two alternative accounts dealing with the relationship between selective attention and object integration. To this end, we investigated hemifield-specific object groupings in a sample of 11 patients suffering from visual extinction (Nowack, Finke, Biel, Keller, Müller & Conci, 2021).

First, we replicated basic findings of Mattingley et al. (1997) showing that when bilateral target segments were not arranged to form a coherent whole Kanizsa figure across both hemifields, patients tended to miss targets on the left side frequently. However, performance improved significantly whenever segments could be grouped to form a complete illusory diamond shape spanning across both hemifields. As in Mattingley et al. (1997), this finding shows once more that the completion of a coherent global object effectively reduces extinction in the impaired, unattended hemifield. According to Mattingley and colleagues, the preserved access to complete objects despite severe deficits of attention in one hemifield thus seems to support the object-based view of attention (Driver & Baylis, 1998; Scholl, 2001; Humphreys, 2016).

Importantly, our results showed that such an amelioration of extinction in bilateral displays only took place when the illusory object extended across both hemifields such that attentional spreading from the attended into the ignored visual hemifield could occur within the boundaries of the grouped percept. However, patients had severe difficulties in detecting left-sided targets in bilateral trials when the target was embedded in an illusory triangle configuration in the left hemifield. This shows that the second, non-salient (but task relevant) target in the attended hemifield hampered target detection in the impaired, unattended hemifield, despite the latter consisting of a salient illusory triangle figure. Hence, our result also supports the notion that grouped objects do not capture attention while it is engaged elsewhere since attention plays a crucial role for triggering the integration of fragments into whole percepts (see also Mack, Tang, Tuma, Kahn & Rock, 1992; Schwarzkopf & Rees, 2011; Conci et al., 2018).

In unilateral left displays (that is, displays with no task relevant target in the attended hemifield), patients detected the left-sided targets better when they were embedded in an illusory figure (i.e., left triangle or diamond) compared to an ungrouped element arrangement. Thus, neglect patients are able to integrate fragmented parts into a global percept even when presented in the unattended hemispace since the lack of a second, task-relevant target in the attended hemifield enables attentional resources to reorient from the attended into the neglected visual field. This reorientation process thus appears to initiate the integration of the object and the integrated shape subsequently enhances the saliency and hence its detectability.

3.1.2. PROJECT 2

The second project of this thesis used a visual search paradigm to investigate whether the integration of separate parts into a whole percept varies with the amount of available attentional resources. To this end, we performed two experiments. In the first experiment, we asked 30 participants to keep their eyes on a central fixation cross while searching for a grouped (vs. ungrouped) target among distractors at three different eccentricities left and right of the fixation cross. In the second experiement, we additionally engaged attention in the center with a second, foveal line-discrimination task while presenting grouped (vs. ungrouped) targets on the intermediate position of the search array to a new sample of 30 participants. Response accuracies and changes in pupil size were analyzed in both experiments.

Results of the first experiment showed that grouped targets which appeared closer to fixation were detected with higher probability than targets which appeared on positions further in the periphery. For the ungrouped targets, no comparable benefit was found, and performance was comparably bad overall (as compared to grouped targets). Regarding pupil size changes, we found that pupils were more dilated for grouped targets appearing at positions that are more distant as compared to smaller pupil sizes for more central locations (for ungrouped targets, the pupils were comparably large irrespective of the location). In summary, this first experiment showed that attention seems to scale with the concurrent grouping demands: grouped targets at central positions induce a relatively narrow focus of attention (i.e. small pupils) and can be easily detected, while more distant grouped targets necessitate a relatively broad tuning of attention but are still detected with low accuracy. We assumed that, initially, the attentional focus was set broadly in order to be able to pay attention to all three locations in both hemifields concomitant with a relatively low resolution. After scanning the display array with this broadly tuned attention, the subsequent integration process of a coherent object triggers the narrowing of the attentional focus, thereby enhancing the resolution (and performance, see Shepherd & Müller, 1989). Hence, if a sufficient amount of attentional resources is available at the location of the to-be grouped item, object grouping processes can be triggered (see also Nowack et al., 2021).

The second experiment revealed that performance was affected by the additional, attention-demanding foveal task. Nevertheless, the grouping benefit persisted irrespective of the additional load. This finding shows that perceptual grouping can still lead to an advantage even when only limited attentional resources are available. Pupil size measures mirrored the behavioral findings: under dual-task conditions, pupil sizes were smaller due to the high attentional load at the fovea, thus indicating a narrow focus of attention, as compared to single task conditions in which more attentional resources were available in order to process targets in the periphery. Moreover, grouped targets were not only easier to detect but also summoned attentional resources more efficiently (i.e., smaller pupil sizes) than ungrouped targets. Thus, grouping processes facilitate detection and modulate the allocation of attention even when only limited attentional resources are available.

Together, our results from Experiment 1 and 2 thus indicate that the integration of fragmented image parts, as well as search guidance by salient, integrated objects scale with the availability of attentional resources.

3.1.3. PROJECT 3

The third project was intended to provide further evidence for the causal role of selective attention for object integration and to replicate findings reported with neglect patients from the study by Nowack et al. (2021), that is the first project of this dissertation, and extend them to healthy participants. To this end, we made use of repetitive transcranial magnetic stimulation (rTMS), which was applied over the right intraparietal sulcus in order to induce neglect-like extinction behavior while participants were asked to detect targets in the left and/or right hemifield. These targets were again embedded in different Kanizsa-type objects similar to the ones used in Nowack et al. (2021).

First, our results showed that the detection of unilateral targets was improved whenever the targets could be grouped together to form a salient Kanizsa triangle in one of the hemifields indicating that salient object groupings improve target processing (see for example Rauschenberger & Yantis, 2001; Conci et al., 2007, 2009; Wiegand et al., 2015; Kimchi et al., 2016; Nie et al., 2016). The detection of the very same target in the triangle, however, was compromised whenever two bilateral targets were presented simultaneously (i.e., one in each hemifield). Thus, participants missed one of the two targets, likely the non-integrated target in favor of the salient triangle in the other hemifield. Interestingly, however, performance in ungrouped and diamond configurations did not suffer from bilateral target presentations presumably because attention was not biased towards one hemifield and could therefore be allocated across the whole display. This pattern is overall comparable to the neglect patients' data (see Nowack et al., 2021 and the first chapter of this dissertation), showing that if attention is currently needed to process information in one hemifield, other objects are likely to be missed. If attention is not currently engaged elsewhere, however, then grouping can increase the saliency of a given target, thereby enhancing search efficiency, and improving target detectability (Conci et al., 2007; Conci, Töllner, Leszczynski, & Müller, 2011; Wiegand et al., 2015; Nie, Maurer, Müller, & Conci, 2016). In the current study, participants' attention could be equally distributed across the whole display, indicating that attention was available to bind fragmentary parts into a coherent whole object in the first place and this salient integrated percept in turn could have drawn attentional resources (see Nowack et al., 2021).

While we could not see any effect of the rTMS stimulation of the parietal cortex in the whole sample, explorative analyses revealed a subgroup of observers who showed a negative effect of IPS stimulation on accuracy as compared to the active baseline stimulation ("IPS-cost") and a second subgroup of observers who showed the opposite pattern, namely, a positive effect ("IPS-benefit"). The IPS-cost was only evident in bilateral trials: when participants were presented with triangle configurations, they missed one of the two bilateral targets. More precisely, we found a hemifield-specific disadvantage of detecting targets in the left hemifield after IPS stimulation comparable to the extinction behavior observable in neglect patients. The IPS-benefit subgroup, on the other hand, showed more accurate detections in bilateral trials for all configurations. Hence, in this subgroup, IPS stimulation seems to have facilitated the allocation and spreading of attention across the whole display, which improved performance overall. Together, our results extend previous findings in neglect patients and indicate that the IPS plays an important role in the attentional selection and processing of salient, integrated objects by influencing the allocation of attention.

3.2. KEY IMPLICATIONS ACROSS PROJECTS

Employing various behavioral and neuroscientific methods in healthy participants and using a sample of neuropsychological patients, this dissertation investigated the relationship between visual selective attention and object integration. When considering the vast amount of literature concerning this topic, it becomes evident that there are two major opposing theories stating that object integration either takes place prior to the engagement of attention (Humphreys et al., 1994; Mattingley et al., 1997; Driver & Baylis, 1998; Scholl, 2001) or that attention is necessary for successful binding of visual parts into a coherent whole object (Treisman & Gelade, 1980; Kahneman et al., 1992; Wolfe & Cave, 1999).

Overall, the presented research projects emphasize the assumption that attention is indeed the catalyst necessary to trigger the process of object integration. As seen in the first project, patients were not able to detect targets in the salient, illusory triangle figure in the unattended hemifield when attention was currently engaged in the other display half. However, when the illusory figure was spanning across the whole display, attention could spread from the attended hemifield along the borders of the illusory diamond into the unattended side (see also Conci et al., 2018). Results of the second project showed that participants, who did not have any deficit in attentional processing, initially had a broad tuning of attention (concomitant with a low resolution), which enabled the process of binding together the image parts into the grouped target figure in the periphery. This salient Kanizsa target in turn attracted attentional resources (especially when the target appeared relatively close to the center) and thus, improved the detection performance (see also Gurnsey et al., 1992; Davis & Driver, 1994; Rauschenberger & Yantis, 2001; Senkowski et al., 2005; Conci et al., 2007, 2009; Wiegand et al., 2015; Kimchi et al., 2016). This grouping benefit was also observable even when the participants' attention was largely bound to the second, central task. Since participants were told to simultaneously perform the central task and search for the targets in the periphery, they should have saved at least some attentional resources for the lateral search task. Accordingly, only residual attentional resources seem to suffice in triggering the object integration process where the integrated objects in turn act like a saliency signal that summons attention. The third project is also in line with the above-mentioned findings showing that the intraparietal sulcus, which is part of the attentional network in the brain, seems to modulate the processing of object groupings by up- and down regulating the deployment of attention to spatial regions were to-be-grouped items necessitate attentional resources for object completion.

Taken together, the current results from three projects support the assumption that attention is indeed necessary for successful object integration. Accordingly, guidance of attention by integrated percepts is not possible without attending to the to-be-grouped objects in the first place. This result pattern can, for example, be explained within the framework of the reverse hierarchy theory put forward by Hochstein and Ahissar (2002). They state that individual inducer elements (i.e., in Kanizsa figures the circles with missing segments) would undergo some basic "preattentive" processing in an initial feedforward sweep of processing. This forward hierarchy acts implicitly, while explicit perception begins only at high-level cortex. In this early explicit perception, or "vision at a glance" stage, perception is based on spread attention, that is, large receptive fields, and guessing at details of categorical information. Early high-level perception, therefore, makes a first approximation guess at binding. "Vision with scrutiny", or selective attention, is engaged subsequently in order to add details and thus confirm or correct the initial guess by truthfully binding features into whole percepts via recurrent feedback from higher to lower levels of processing in the visual hierarchy (potentially directed by parietal cortex, see Humphreys, 1998). Concrete evidence for a critical role of the feedback from higher to lower levels of processing in illusory figure perception was provided in a study by Chen, Weidner, Zeng, Fink, Müller, & Conci (2020). They found that the lateral occipital cortex first integrates inputs from multiple neurons in lower-level cortices in order to generate a global shape representation, while more details are subsequently added via feedback to early visual areas. This feedback thus triggers object completion. Intimately connected with this view is the incremental grouping theory by Roelfsema (2006), as it describes the integration of image parts as an attention-depended, time-consuming, and capacity-limited process relying on feedback connections. Together, this implies that an integrated object could pop out and guide attention only after some attention-dependent grouping has generated a complete-object representation. Hence, object completion can be successful when sufficient attentional resources are deployed to those parts of the visual field that could give rise to the perception of an integrated object, but not when the allocation of attention towards these grouping-inducing elements is prevented (e.g., by a task-relevant target that is presented elsewhere).

Considering the current results of this thesis, previous findings of object integration processes in neglect patients do not longer seem to support a preattentive account as proposed by for example Mattingley et al. (1997) but instead speak for the spreading of attention from the attended into the unattended hemifield. Accordingly, the idea that object integration is an attention demanding process contradicts the object-based view. This view suggests that the representation of complete objects arises prior to the engagement of attention (Humphreys et al., 1994; Mattingley et al., 1997; Driver & Baylis, 1998; Scholl, 2001). The feature integration theory by Treisman and Gelade (1980) assumes that attention is necessary, and thus seems more appropriate to explain how features are grouped. This theory, however, acts on the assumption that selective attention must first be allocated to a given stimulus in order to enable the integration of featural parts into complete-object representations. Our results, are more consistent with the early high-level perception account (which makes a first approximation guess at binding) as proposed by Hochstein and Ahissar (2002), suggesting that object integration processes can already be triggered by spread attention.

3.3. METHODOLOGICAL CONSIDERATIONS AND FUTURE DIRECTIONS

This thesis successfully combined behavioral measurements with neuroscientific methods such as pupillometry (Project 2) and TMS (Project 3). While these additional assessments provided substantial information on the relevant neurophysiological processes underlying the involvement of attention in perception and object integration, they also have their limitations. This section therefore discusses the most relevant methodological considerations regarding pupillometry and TMS.

3.3.1. PUPILLOMETRY

The behavioral results of our second project showed a performance benefit for grouped (relative to ungrouped) targets, which additionally increased with decreasing distance from fixation. The analysis of the pupillometry data essentially mirrored these results suggesting that the size of the pupil flexibly adapts to changes in attentional breadth (see also Daniels et al., 2012; Brocher et al., 2018; Ivanov et al., 2019; Mathôt & Ivanov, 2019; Mathôt, 2020). One major limitation of some of the above-mentioned studies, however, is that task difficulty also affects pupil size. Hence, changes of attentional breadth might be directly entangled with differences in task difficulty for example due to larger eccentricities which usually elicit poorer performance than more proximal ones independently of their configuration on grounds of visual acuity (see Carrasco, 2011 for a review).

In our first experiment, however, we found no significant difference in performance and pupil size for ungrouped target configurations across all three eccentricities. There was an eccentricity-dependent effect only for the grouped targets, which renders it unlikely that the results are due to an overall gradient of visual acuity and thus higher difficulty for larger eccentricities. Moreover, we made sure to only analyze correctly identified trials in the pupil size analysis while trials with incorrect behavioral responses were discarded from the data. Thus, all analyzed trials, irrespective of variable eccentricity, were equally likely to be detected. Additionally, in the second experiment, we only presented targets on the intermediate position to control for potential influences from crowding effects and differences in task difficulty due to variable target eccentricities.

Together, we argue that the size of the pupil indeed only represents changes in attentional breadth in our experiments. Future studies also should make sure that task difficulty is carefully controlled for in the design in order to understand how grouping and eccentricity interact in their effects on accuracy and pupil size independent of task difficulty. One additional possibility might be to enlarge the stimulus size at different eccentricities according to the cortical magnification factor in order to correct for poorer spatial resolution and thus visual acuity and task difficulty at further peripheral locations (see Carrasco, 2011).

3.3.2. TMS

While the behavioral results of our TMS study were in general compatible with the assumption that object grouping requires attention, the concurrent TMS stimulation during the experiment did not show an overall effect upon performance. This could be explained by the high variability of the neglect syndrome, which is typically observed after large and variable right-sided damage in parietal regions: such damage is often reported as lesions which are extending into temporal, occipital, and frontal cortex, and may even spread into subcortical structures (Vallar & Perani, 1986; Kerkhoff, 2001; Karnath et al., 2002). The severity of behavioral symptoms is also known to differ quite substantially across individuals as a function of the location and size of the brain damage (Kerkhoff, 2001; Sack, 2010). Hence, quite a diverse range of lesions may lead to diverse clinical signs of neglect. Furthermore, various studies inducing neglect-like symptoms with TMS also differ quite substantially in terms of localization accuracy and the specific areas in parietal cortex which were stimulated (e.g. Pascual-Leone, Gomez-Tortosa, Grafman, Always, Nichelli, & Hallett, 1994; Fierro, Brighina, Oliveri, Piazza, La Bua, Buffa, & Bisiach, 2000; Hung, Driver, & Walsh, 2005;

Koch, Oliveri, Torriero, & Caltagirone, 2005; Ricci, Salatino, Li, Funk, Logan, Mu, Johnson, Bohning, & George, 2012; Donaldson, Rinehart, & Enticott, 2015; see also Driver et al., 2010; Sack, 2010, for reviews). Future studies using TMS to induce neglect-like behavior for investigating the relationship between selective attention and object integration could therefore try to stimulate other areas, such as the temporoparietal junction (TPJ). Damage to the right side of this brain region is also known to play a critical role in causing neglect (for a review see Vandenberghe, Molenberghs, & Gillebert, 2012). Moreover, since our analyses did not reveal any TMS effect across the whole sample, we additionally concentrated on individual effect patterns by means of explorative analyses. Our results and interpretations should therefore be appreciated with this limitation in mind. Future studies with a directed hypothesis are necessary to confirm our explorative results.

3.4. CONCLUSION

This thesis identified systematic associations between perceptual integration processes and visual selective attention. We showed that in neglect patients with associated extinction behavior, object completion can be successful when sufficient attentional resources are directed to those parts of the visual field that could give rise to the perception of an integrated object, but not when the allocation of attention towards these grouping-inducing elements is prevented. In healthy participants without any deficits of attentional functioning, we demonstrated with the help of pupillometry that perceptual grouping scales with the allocation of attention even when only residual attentional resources are available to trigger the representation of a complete (target) object, thus illustrating that object completion operates in the “near absence” of attention. In another group of healthy volunteers, who were stimulated with TMS, we found that the parietal cortex seems to modulate the processing of object groupings by up- and down regulating the deployment of attention to spatial regions were to-be-grouped items necessitate attentional resources for object completion. Overall, this thesis complements research on the relationship between selective attention and object integration and supports the view that part-to-whole object integration and search guidance by salient, integrated objects require attentional resources in the first place. Applying neuroscientific methods in addition to behavioral measures in healthy participants depicts a promising approach for investigating neuro-cognitive mechanisms of the role of selective attention in object integration apart from results found in neuropsychological patients.

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Journal Articles

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Conference Abstracts

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AUTHOR CONTRIBUTIONS

Chapter 2.1.

The author of this dissertation collected data and analyzed the data, created plots and interpreted the results, and wrote the manuscript.

Kathrin Finke designed the experiment and helped revising the manuscript.

Anna Lena Biel helped with collecting data and commented on the manuscript.

Ingo Keller recruited the participants, examined medical records and confirmed the diagnostic status of participants. He also created the lesion mapping figure.

Hermann J. Müller commented on and helped revise the manuscript.

Markus Conci designed, programmed and supervised the experiment. He also contributed to the interpretation of the results and critically revised the manuscript.

Chapter 2.2.

The author of this dissertation designed and programmed the experiment, collected and analyzed the data, created plots and interpreted the results, and wrote the manuscript.

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The author of this dissertation designed and programmed the experiment, collected and analyzed the data, created plots and interpreted the results, and wrote the manuscript.

Paul Taylor counseled and trained the author in TMS. He contributed to the interpretation of the results and critically revised the manuscript.

Kathrin Finke critically revised the manuscript.

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